VERITAY
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AD-A187 208

LIQUID GUN DIAGNOSTICS

Robert L. Talley, Principal Investigator
Veritay Technology, Inc.
4845 Millersport Highway
P.O. 305
East Amherst, New York 14051

June 30, 1987

Scientific and Technical Report (Final) (CDRL A002)
Period Covered: 18 Sept 1986 to 18 March 1987
Contract No. DAAA21-86-C-0233

Veritay Report No. AO5-87-1F

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Prepared for

Department of the Army, U.S. Army AMCCOM
AMSMC-PCW-C(D)
Dover, NJ 07801-5001

10 20 55

MIL-STD-847B
7 November 1983

ADA187208

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
Unclassified	

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
N/A	As Per Contract
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
N/A	

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
V-A05-87-1F	

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
Veritay Technology, Inc.		U,S, Army AMCCOM, AMSMC-PCW-C (D)

6c. ADDRESS (City, State and ZIP Code)	7b. ADDRESS (City, State and ZIP Code)
4845 Millersport Highway P.O. Box 305 East Amherst, New York 14051	Dover, NJ 07801-0233

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
U.S. Army AMCCOM	W15QKN	DAAA21-86-C-0233

8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS			
Dept. of the Army U.S. Army AMCCOM/AMSMC-PCW-C (P) Dover, NJ 07801-5001	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11. TITLE (Include Security Classification)
Liquid Gun Diagnostics

12. PERSONAL AUTHOR(S)
Talley, Robert L.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 9/18/86 TO 3/18/87	87/6/30	68

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Liquid Propellant Guns (cont. on reverse)
			Diagnostic Techniques

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This Phase I effort is to improve the state of liquid gun performance characterization and diagnostics by developing a suitable combination of conventional and new sensors for visualizing selected internal hydrodynamic and combustion phenomena and evaluating their associated parameters quantitatively. Particular attention was given to the use of high speed photographic techniques for improved visualization, and to the simultaneous use of pressure and thermal sensors to obtain quantitative measures.

An available 25 mm liquid propellant (LP) ignition test fixture was redesigned, modified and put into service as a working LP gun fixture to attain gun firing conditions for instrumentation feasibility tests. Twenty (20) such tests were conducted to explore selected techniques. During the

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐	U

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL

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PREFACE

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Section 1.0

INTRODUCTION

The feasibility investigation to develop an instrumentation configuration for enhanced diagnostics of liquid propellant guns (LPG) reported here was initiated on 18 September, 1986, and conducted by Veritay Technology, Inc., for U.S. Army AMCCOM, Dover, New Jersey.

A recognized need exists for practical diagnostic methods to characterize liquid propellant gun phenomenology, and particularly those features associated with normal performance as well as with an occasional erratic behavior. Specific diagnostic information on the evolution of internal combustion phenomena is relatively scarce. A set of techniques of special interest includes those for direct visualization of the temporal and spatial behavior of ignition, combustion, and fluid flow under typical LP gun firing conditions.

The objective of this program, therefore, was to improve the state of LPG performance characterization and diagnostics by developing a suitable combination of conventional and perhaps new type sensors suitable for visualizing selected internal phenomena and evaluating their associated parameters quantitatively. Particular attention was given to the use of photographic techniques for improved visualization, and to the simultaneous use of pressure and thermal sensors to obtain quantitative measures.

The approach of this program was theoretical-experimental and it stressed the conceptualization, design, and development of a suitable instrumentation configuration. This process also included feasibility testing of the configuration

under live firing conditions using a 25mm LP ignition test fixture initiated with a pyrotechnic igniter. This fixture is a modified form of a fixture used previously at Veritay for 240 successful LP test firings.

Overall guidance in the selection of components of the diagnostics instrumentation configuration was provided by past and current LP investigations at Veritay and elsewhere. Preferred techniques were to be suitable for employment in statically loaded, dynamically loaded and regenerative type LP systems using either liquid monopropellants or bipropellants. Further, the techniques selected may also be applicable to electro-thermal type gun systems (such as the electrically generated plasma-water, or plasma-oxidizer, or plasma-fuel and oxidizer types) because of their similarity to LP gun systems with electrical ignition. The configuration selected under this Phase I program is expected to serve as a baseline instrumentation system; it is expected to undergo further development in order to better quantify and understand LP phenomena.

This report discusses the various features of the investigation indicating the LP phenomena known to be of concern, the measures desired, the instrumentation configuration selected as baseline, the results obtained, the evaluations made, and follow-on work recommended to further the utility of this scheme.

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Section 2.0

INVESTIGATIVE PROGRAM

A theoretical-experimental approach which stressed the
relevant phenomena associated with LP gun performance combined
with direct experience in LP gun development at Veritay was used
to explore the suitability of various sensors for LP diagnostics.
An instrumentation set was selected and assembled to enable
measurements to be made of the key phenomena. A 25mm LP ignition
fixture available at Veritay was extensively modified for
diagnostics to enable shakedown and ballistic testing of the
selected combination of instruments. Once the tests were
conducted, the results were reviewed and evaluated to select a
final baseline set of sensors.

The program was divided into the following tasks:

1.   Review phenomena associated with LP
      gun performance.

2.   Determine an initial design of the
      overall instrumentation configuration
      including specification and selection
      of sensors and elements.

3.   Modify the LPG test fixture.

4.   Construct the optical train and mounts
      for a high-speed camera.

5.   Fabricate the electronics system to
      time and control the instrumentation
      and gun system operation.

6. Fabricate miniaturized thermal sensors.

7. Assemble the overall system and conduct shakedown tests.

8. Evaluate configuration design and modify if necessary.

9. Conduct ballistic tests involving the complete configuration and data acquisition facilities.

10. Evaluate the test results emphasizing diagnostic system performance and suitability of the data.

Section 3.0

LIQUID PROPELLANT GUN PHENOMENOLOGY FOR INVESTIGATION

Past liquid propellant gun programs have often been conducted in a traditional manner by placing primary emphasis on developing and refining hardware and conducting firing tests where changes in hardware or mode of ignition were evaluated in terms of ballistic performance. Ballistic performance in most gun development programs is based on measured pressure and projectile muzzle velocity.

The emphasis on hardware development is necessary at the beginning of most such programs to bring the state of development to a level where variation of parameters can be studied in a meaningful way. However, to achieve an increased understanding of the phenomena that comprise the ballistic cycle and a better definition of the controlling parameters required to further the LPG development, more extensive diagnostic techniques and investigations need to be employed.

An important feature in such diagnostic investigations is that selected experimental techniques can be applied to help isolate phenomena that occur during the ballistic cycle. We believe, for example that firing a gun, or an ignition test fixture can sometimes mask the individual contributions of a parameter. Often, it is most productive and convenient to use a specially designed fixture that is tailored to investigate the phenomena or parameter of interest. In the next section, Section 4.0, "Experimental Firing Configurations," both an LP ignition test fixture, and a transparent injection fixture are introduced. The latter is a special fixture of the type just noted, used in this program to facilitate examination and study of LP injection into a combustion chamber.

Since 1975, an experience base has been assembled by Veritay for liquid propellants; of particular importance are the data assembled on the phenomenology of LP ignition and combustion. On this basis, we believe that the main physicochemical phenomena involved in liquid propellant gun performance that are of potential diagnostic interest here are those associated with the processes of liquid propellant loading or injection into a gun chamber, propellant ignition and combustion in the chamber, possible travelling-charge-type combustion in the barrel, and related hydrodynamic effects such as wave motion, liquid breakup, compression-relaxation, flow, and mixing.

LP injection constitutes an important step in both regeneratively and dynamically loaded systems. In the former, LP injection occurs following initial ignition, is continuous from an LP reservoir behind a moving piston through one or more orifices into the chamber, and is driven by a pressure developed by the LP combustion itself on the chamber side of the piston. The key injection phenomena of interest include both non-combustion and combustion-related items. The former includes the overall nature and flow dynamics of the liquid spray injected into the combustion chamber such as its spatial and temporal distributions of droplet size, bulk density, velocity, and how these are influenced by the changing geometry and dynamics in the gun fixture. Combustion complicates the situation, since spray burning with attendant heat release and gas generation gives rise to thermal effects such as droplet heating, surface vaporization and possible drop disintegration, as well as to pressure waves in the chamber, which may cause redistribution of the spray parameters including spray drop size via secondary atomization. Most of the known work with the regenerative systems have involved the use of monopropellants. It is possible that bipropellants could be used in such a system, but whether the gains which might be achieved in combustion control and stability

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would outweigh additional complications likely to be associated with injecting a bipropellant remain to be seen.

For dynamically loaded systems, the liquid propellant is completely loaded into the combustion chamber by use of an outside pump before the LP is ignited. In this type of system, the injection phenomena of interest depend significantly on whether a monopropellant or bipropellant is used. In either case, however, attention needs to be given to the handling of ullage air during injection. At least two approaches are known. In the first, an attempt is made to minimize the amount of initial ullage by using a chamber with movable projectile or breech bolt, which is in a near zero ullage condition initially and expands with the amount of LP injected. The second uses a flow-mixing scheme, whereby the air (and LP vapor) is redistributed into bubbles so small that their contribution to adiabatic heating and ignition effects are negligible.

With a monopropellant, other features of injection (except perhaps short-term cavitation and total time of injection) are of little consequence. With a bipropellant, the key injection phenomena of interest include for both fuel drops and air bubbles their spatial and temporal distribution of particle size, bulk density and the stability of the three-phase dispersion in the combustion chamber. Other relevant parameters include the oxidizer-to-fuel volume ratio, the injection characteristics, and operating conditions and the pressure to which the final injection products and ullage air are compressed at the end of the injection cycle. This last compression step has an important influence on the significance of ullage air and its subsequent behavior during combustion.

The ignition process in LP gun systems is rather critical to ensure that the overall LP combustion is started

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smoothly and properly. Exactly how to accomplish "proper" ignition is still a subject of active investigation.

The ignition process, and, more particularly, the igniter can be characterized by a variety of parameters including energy output, the action time, the ratio of the average energy value to the peak value, the mode by which the ignition or energy transfer occurs, the geometry of the igniter and the pressure output of the igniter. The mode by which ignition occurs is governed by the amount of gas that is generated by the igniter, the hot particles, electrical heating, radiation or chemical heating.

Some of the early LP work on statically loaded monopropellants (with which Veritay personnel were associated) involved an electrical igniter that was housed in a staged precombustion chamber. The duration of the electrical discharge was less than 200 microseconds; a typical discharge consisted of a 30-microsecond formative phase followed by roughly a 150-microsecond arc discharge. In this early work, very high energy levels were required to ignite the NOS365 propellant. This short-duration, high-energy output developed high pressures inside the precombustion chamber and resulted in an unsteady hydrodynamic pressure wave along the length of the chamber. Some 400 microseconds were required for this wave to traverse the 6-inch (approximately 150mm) chamber length, reflect off the projectile base and return to the burning gas-liquid interface. By this time the igniter had completely terminated its function. Subsequent pressure wave reflections strongly suggested that the return waves caused spallation to occur at the interface. This spallation, in turn, created droplets, which caused an abrupt increase in combustion and pressure pulses sympathetic with the incoming waves. It was concluded that to reduce such hydrodynamic wave effects it would be desirable to use an igniter which exhibited a rather long, gentle functioning cycle. As a

result, a pyrotechnic igniter was viewed with some favor, since it can be formulated to (1) function over a relatively long period of time; (2) generate a large amount of gas, independent of the main propellant charge; and (3) provide hot particles to aid in local ignition of the propellant at various positions along the gas-liquid interface.

In subsequent work at Veritay, pyrotechnic igniters were found to behave much as anticipated, and have been used for LP ignition under this effort.

For this program, the igniter used consisted of a conventional small rifle primer CCI 400 (although others have also been used successfully in other work) together with a 3.86-grain (0.25-gram) booster charge of Hercules Bullseye smokeless powder. These were loaded into a steel cartridge case with a 0.213-inch (5.41mm) diameter gas ejection orifice. A 0.25-inch (6.35 mm) polyethylene ball was force fitted into the front of the cartridge case to provide a liquid seal against the final pressure of the LP injected into the chamber.

This particular igniter configuration has been employed .with some success in achieving LP ignition in the test fixture used here. This will be noted later in this report in results showing pressure-time curves taken in the chamber of this fixture.

Coupling of the igniter output to the liquid propellant charge of the main chamber in a dynamically loaded system has received attention in past work, but remains a topic for further exploration.

In addition to the type, size and activity of the igniter indicated earlier, the coupling also depends on the geometry of any precombustion chamber associated with the igniter

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and the geometry of the breech end of the chamber itself. For the early monopropellant tests noted previously, the precombustion chamber was a rather small volume at the breech end of the chamber. It was connected to the chamber in a discontinuous fashion so that any flow coming from the precombustion chamber was exposed to a 90-degree bend. As a result, the surface area of the gas volume was not controlled. Indications were that this led to the formation of ring vortices and mixing inside the chamber. In cases where the igniter output was insufficient to achieve immediate ignition of the main LP charge, extended mixing occurred, which eventually led to extremely rapid combustion and extremely high overpressure. By connecting the precombustion chamber to the main chamber with a conical angle, some control was achieved over the growth of the gas volume.

Later investigations at Veritay have generally given results that are consistent with the earlier findings. There are indications, however, that breech and igniter geometries must be considered together with igniter strength and its tendency to generate hydrodynamic pressure waves to achieve a more complete basis for understanding the coupling. The geometry and stability of the initial gas volume in the main LP charge generated by igniter gas ejection appears to be a rather important consideration to the early stages of coupling.

Recent findings under other programs at Veritay, involving dynamic loading of bipropellant, suggest that several features of the main charge must also be included in considerations of igniter-charge coupling. As a minimum these appear to involve the state of the ullage air on the chamber at the time of ignition, the oxidizer-to-fuel ratio of the main LP charge in the vicinity of igniter gas output, the droplet sizes of fuel in the charge, and the length of the charge between igniter output and projectile base (which essentially determines

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the time for pressure wave passage lengthwise in the chamber).

While some workable igniter-charge coupling configurations have been achieved experimentally, detailed diagnostics to explore the actual phenomena involved and to learn the key reasons why satisfactory results were obtained have yet to be carried out.

Flash X-rays of liquid propellants at low charge-to-mass ratios taken at Indian Head around 1974-1975 showed the existence of a Taylor cavity, formed as the projectile began to move down the barrel. This finding has more recently been confirmed in investigations conducted at Pennsylvania State University. This cavity formation is one key feature, which may occur for combustion in a dynamically loaded chamber.

As the cavity is formed, it is generally believed that the gas generated by the combustion flows along through the cavity. This gas flow can likely cause Helmholtz instabilities to occur at the liquid-gas interface with subsequent instability growth culminating in spray drop formation. It is not clear whether Taylor instabilities from liquid acceleration normal to this same interface may also contribute to spray formation. If the latter effect is contributory, then another factor in spray generation is available for use in combustion control.

This formation of spray is the envisioned mechanism by which the burning surface area is generated to support the interior ballistics cycle. Corroboration of this view is provided by results of tests conducted with a high viscosity liquid propellant which showed low combustion rates and low peak pressures; this is to be expected since a high viscosity inhibits drop formation and, hence, the generation of a large burning surface area.

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As implied above, Taylor cavity formation may not be the only feature of importance to combustion in a dynamically loaded chamber. Front ignition tests conducted at Veritay suggest that other mechanisms may also be contributory, such as local turbulence together with adiabatically generated heat and attendant LP vaporization throughout the LP charge. Such features are as yet unexplored.

Another combustion feature of potential interest---and one which has been the subject of some skepticism and controversy in LP gun phenomenology---is that of achieving significant LP combustion in the barrel. Such combustion is commonly referred to as "traveling-charge" phenomena. The precise details of how such a traveling-charge effect can be achieved are sketchy, but it appears that a significant amount of unburned liquid propellant needs to be forced into the barrel behind the moving projectile. In turn, combustion in the chamber must continue to move this slug of unburned LP down the barrel, while at the same time, the combustion itself may progress through the slug (perhaps via a Taylor-cavity-type channel) and become intense just behind the projectile. In any case, a relatively high pressure is exerted on the projectile base.

The net result of such a dynamic process is to achieve a higher base pressure on the projectile throughout its travel down the barrel than would occur under more normal circumstances in which most LP combustion is presumed to take place in the main combustion chamber. The enhanced base pressure, of course, would be expected to launch the projectile from the barrel with a higher than normal muzzle velocity.

The several features and phenomena noted here are representative of the items of interest for diagnostic investigation under this program.

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In summary, the measurements that should be made can be rather extensive. The extent to which each measurement should be pursued depends on judgments concerning cost versus expected value of the information obtained, i.e., potential understanding of phenomena. The following should be measured as a function of time:

o   Local pressure
o   Local temperature
o   Location of liquid-gas interfaces
o   Location of the projectile
o   Local heat flux at the chamber surface
o   Local burning surfaces and regions
o   Translation of liquid elements in the chamber
o   Local barrel heating and erosion.

Section 4.0

EXPERIMENTAL FIRING CONFIGURATIONS

4.1 LP Ignition Fixture

Success in establishing an LP diagnostics configuration
depends critically on the ability to use an existing liquid
propellant gun fixture--modified as necessary to render it
suitable for selected sensors--to attain gun firing conditions
for instrumentation feasibility tests. As a result of work at
Veritay on a liquid propellant gun development program supported
by FMC Corporation, Northern Ordnance Division, we had at the
outset of this effort, a 25mm LP ignition test fixture available
for alteration as indicated above.

The actual modifications of the LP ignition fixture
itself were straightforward as expected. Considerably more
extensive revisions and new fabrications of auxiliary equipment
needed to operate the ignition fixture than originally planned
were required to render the overall system suitable for
instrumentation tests. These auxiliary items included the mount,
pump, air drive, LP plumbing, and electronics for control of the
firing and instrumentation timing. The need for most of these
changes stemmed from non-government-funded program findings at
Veritay, after the proposal for this effort was submitted. As a
result, a more suitable LP ignition fixture for instrumentation
exploration and evaluation is now available. This ignition
fixture has been used for six (6) shakedown test firings with
partial instrumentation and fourteen (14) complete ballistic test
firings with more extensive instrumentation. Results and
evaluations of these tests are discussed later in this report.

This fixture, as modified for this effort, is
configured for dynamic loading with liquid bipropellant and is
shown in Figure 1. The general characteristics of this fixture

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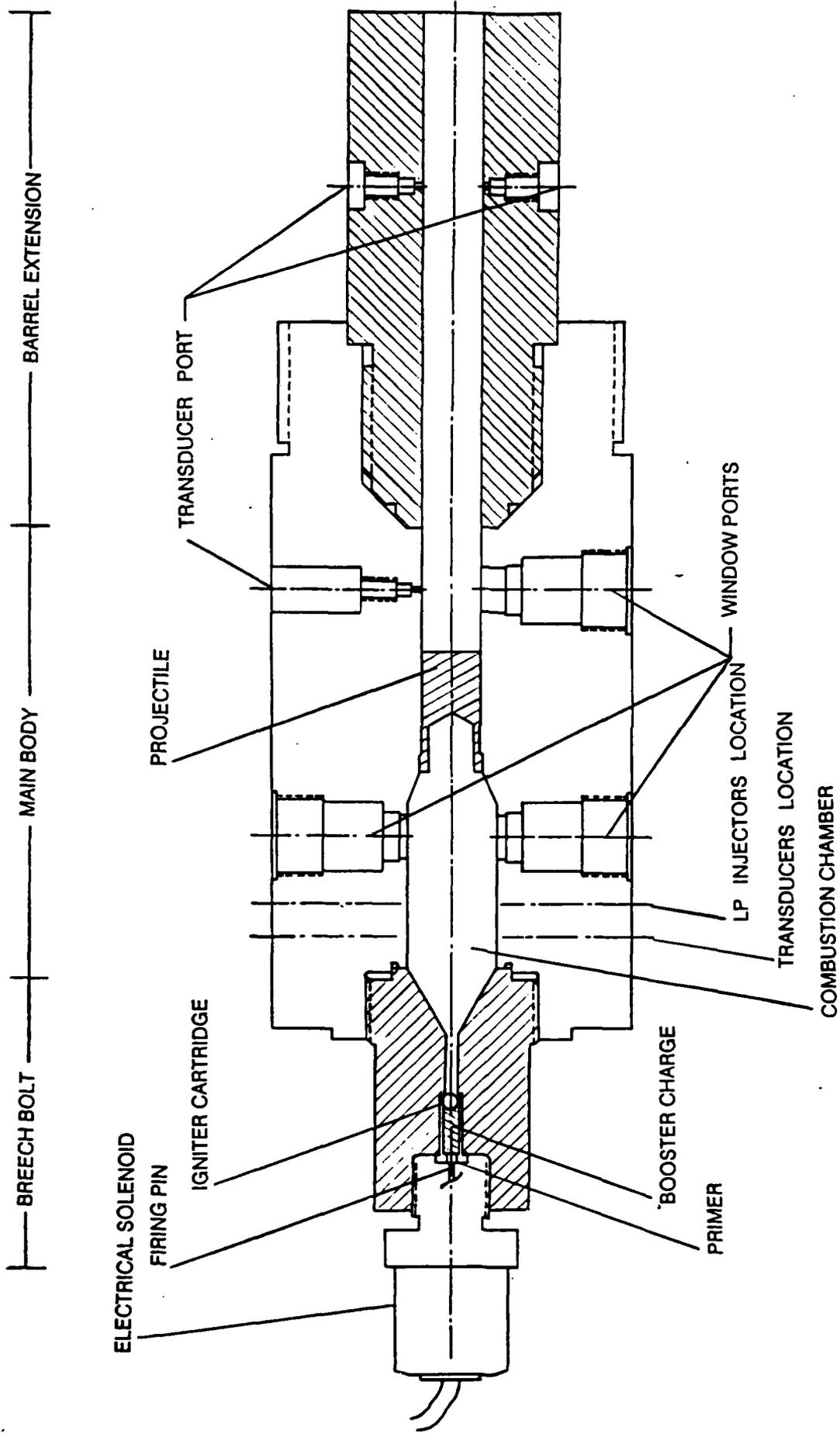
Figure 1. Liquid Propellant Ignition Fixture

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are given in Table 1.

TABLE 1 SUMMARY OF IGNITION FIXTURE CHARACTERISTICS

Feature	English Units	Metric Units
Main Body		
Overall Length	12.000 in	304.8 (-3) m
Outside Diameter	5.945 in	151.0 (-3) m
Chamber		
Diameter	1.500 in	38.10 (-3) m
Length	3.318 in	84.28 (-3) m
Volume	6.308 in^3	103.78 (-6) m^3
Bore		
Diameter	1.030 in	26.16 (-3) m
Length	4.062 in	103.17 (-3) m
Windows		
Plug (acrylic) Diameter	0.750 in	19.05 (-3) m
Sapphire window		
Diameter	1.125 in	28.58 (-3) m
Thickness	1.000 in	25.40 (-3) m
Injectors (2 oxidizer, 1 fuel)		
Bore Inlet Diameter	0.140 in	3.56 (-3) m
Barrel Extension		
Outside Diameter	3.400 in	86.36 (-3) m
Bore		
Diameter	1.030 in	26.16 (-3) m
Length	8.750 in	222.25 (-3) m
Overall Barrel Length	12.812 in	325.42 (-3) m

The ignition fixture essentially consists of three parts: a main body that includes the LP combustion chamber cavity and the first part of the barrel; a barrel extension which provides an overall barrel length of 12.8 inches (325 mm); and a breech bolt with igniter cartridge and electrical firing solenoid.

The chamber itself is basically cylindrical in shape with ends in the form of truncated cones. A flat-nose projectile with a rear cavity (to adjust projectile mass) is shown in

Figure 1 with its shot-start band placed against the barrel
forcing cone just ahead of the chamber.

A barrel extension section is fitted to the front of
the main body to extend the overall barrel length. This
extension section could be easily replaced by a full-length
barrel if desired at some later date.

The breech bolt for this fixture screws into the rear
of the main body and can be easily removed for projectile
loading. When the breech bolt is in place, it forms the rear end
of the combustion chamber. The breech bolt itself contains a
reloadable igniter cartridge consisting of a percussion-type
rifle primer and booster charge. The specific igniter
configuration shown in Figure 1 is not critical, but has been
found in past work to perform well, and was used for all firing-
type diagnostic tests conducted under this program. The igniter
cartridge is sealed from the liquid propellant by a plastic ball.
The ball is loaded with the cartridge from the rear and comes to
rest against a small shoulder of a short precompression tube.
This tube, in turn, is coaxial with the chamber and leads to the
apex of a 60-degree expansion cone that forms the rear of the
chamber.

The chamber is also fitted with three high-pressure
check valves through which liquid oxidizer and fuel are injected
into the chamber. These valves are shown in the cross-sectional
view of Figure 2. A dump valve port is also indicated in
Figure 2, as such a valve is necessary to enable the chamber to
be safely emptied of LP for nonfiring injection tests or for
misfires.

Additional auxiliary equipment is, of course, required
to operate the LP ignition fixture. A diagram of the liquid
propellant pumping system used is given in Figure 3.

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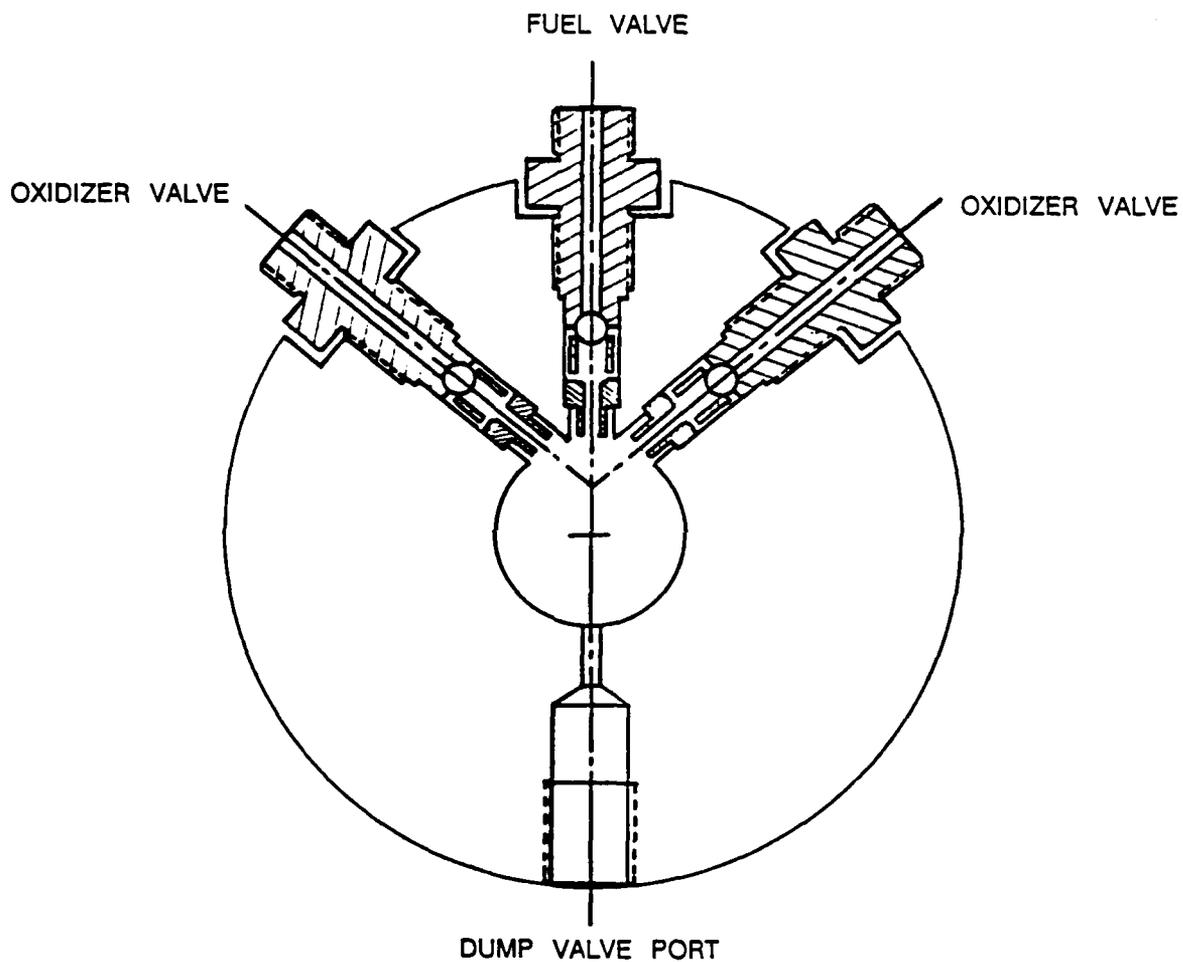
Figure 2. Cross Section of Ignition Fixture at Injection Valves

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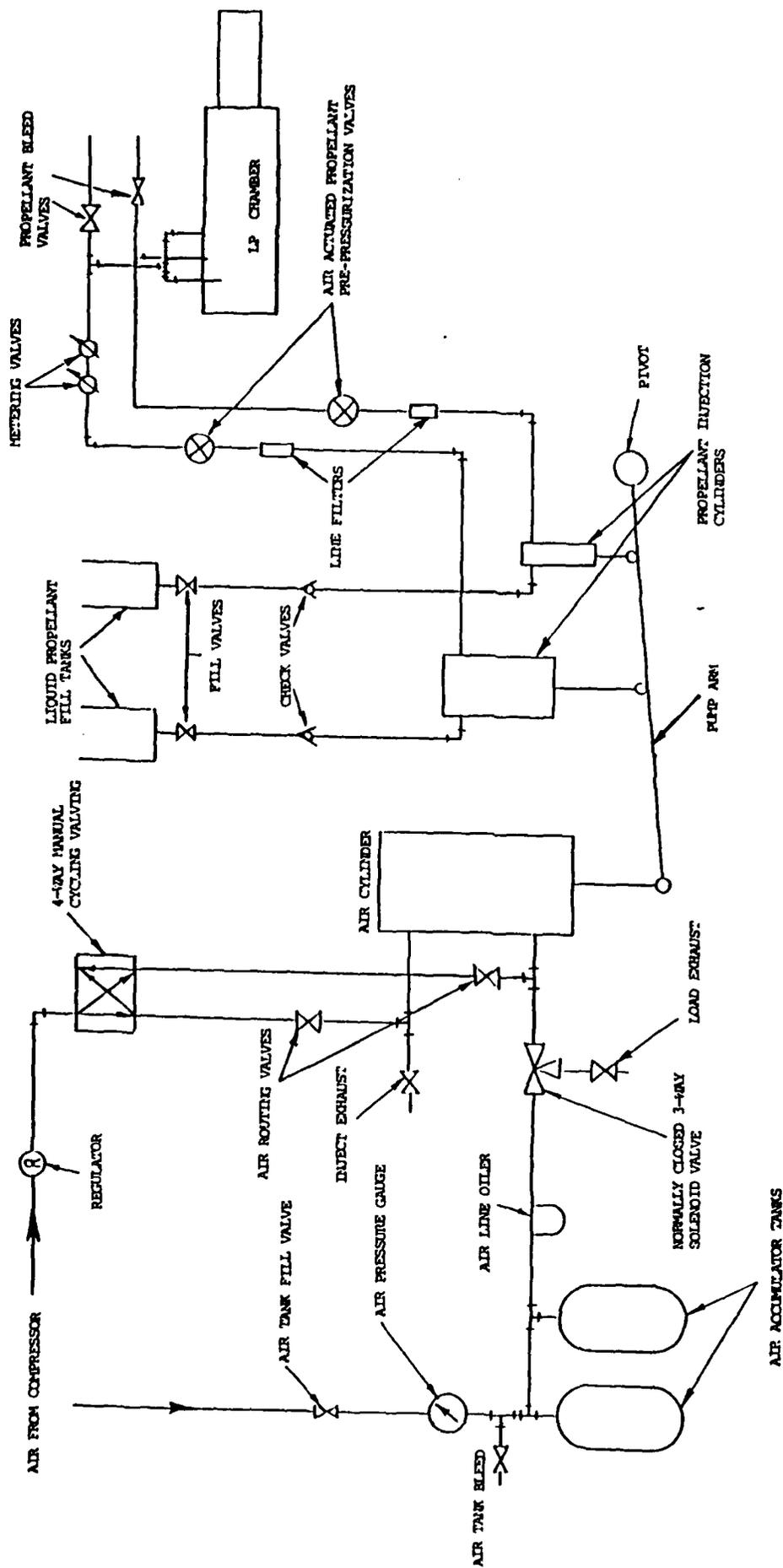
Figure 3. Liquid Propellant Pumping System

A photograph of the ignition fixture together with barrel extension, window retainer rings and injector valves, but without sensors or breech plug are shown in Figure 4. The overall fixture mount and air accumulator tanks used to drive the air-actuated pump are shown in Figure 5. The pump, designed for test convenience, consists of a 6-inch diameter air cylinder, which drives one end of a moveable arm about a fixed pivot point. Oxidizer and fuel drive cylinders have their piston rods fastened to the arm, as shown in Figure 6, at distances from the pivot selected to give a specific oxidizer-to-fuel (O/F) volume ratio. This ratio can be adjusted by repositioning one or both of the oxidizer and fuel piston rod connection points to the arm. This liquid propellant pump arrangement is a constant displacement type system in which the pressures upstream of the oxidizer and fuel injectors generally differ from each other.
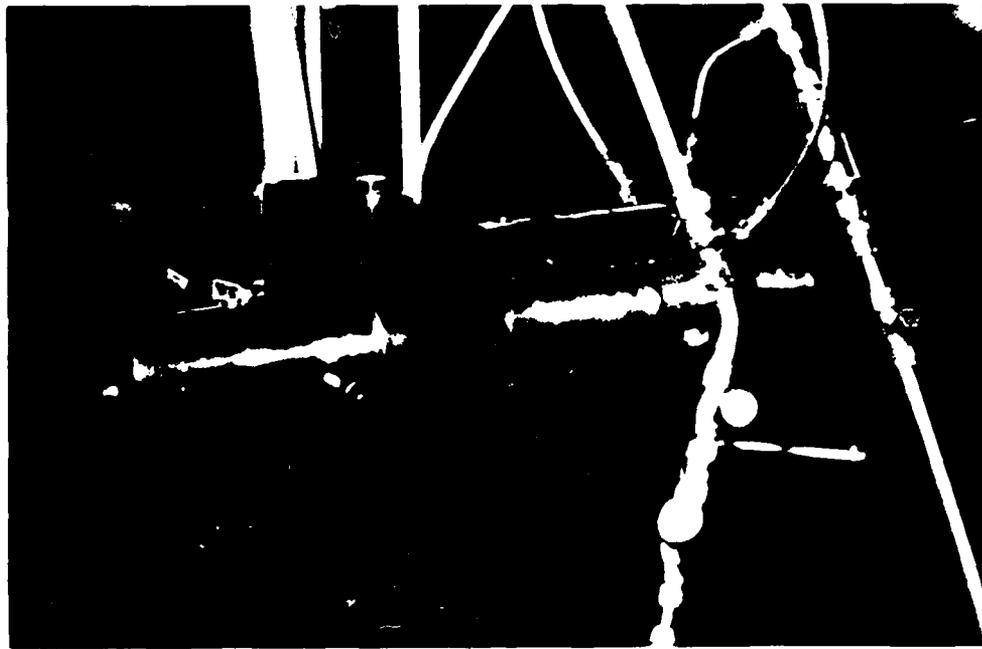

Figure 4. 25mm LP Ignition Fixture

< Figure 5. Air Accumu-
lator Tanks to Drive LP
Pump

Figure 6. Air Driven Liquid >
Propellant Pump
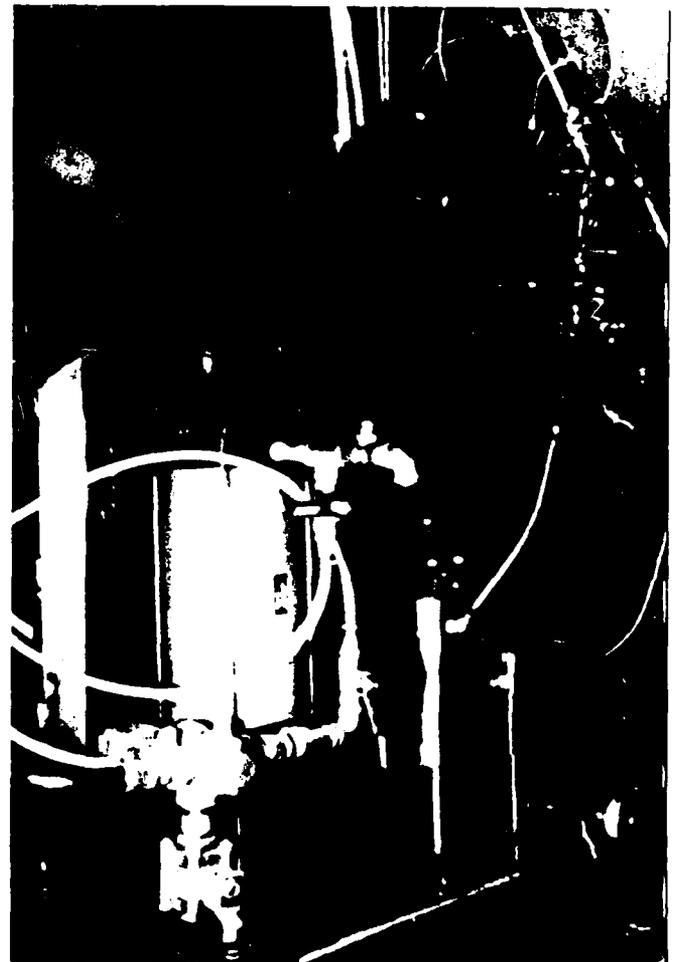
The overall system used to control the various sequences of operations required to dynamically inject the LP, cycle through the safety interlocks, activate the instrumentation, and fire the test fixture is discussed later in Section 5.6 "Computer-Controlled Firing and Instrumentation." A new computer-controlled system was designed, configured and employed for all the test firings conducted under this program as part of the instrumentation configuration. While such a system is perhaps not an absolute necessity for LP gun diagnostics activities, the flexibility, accuracy and efficiency, which it has provided under this program strongly indicates that computer control of complicated firing tests can contribute greatly to the success of such operations.

Operationally, the firing cycle of the LP ignition fixture starts by prepressurizing the air accumulator tanks to a selected pressure. These tanks are then closed to the charging air supply. With flow valves closed and the fuel and oxidizer lines bled free of air, air from the accumulator tank is fed to the air drive cylinder of the pump. The pump responds by prepressurizing the feed liquids against the closed pre-pressurization valves. To this point the liquids have not entered the combustion chamber of the fixture. The air-actuated pre-pressurization valves are then opened and the liquids begin to inject through the high-pressure check valves into the chamber. The speed of injection is controlled by the combination of air pressure in the air drive cylinder of the pump and a preset adjustable needle valve located in the oxidizer line. Injection continues until the back pressure in the fuel line exceeds a preselected injection pressure threshold (somewhat below the fuel drive pressure) and starts a delay timer to actuate the primer solenoid. Finally, when the chamber becomes fully pressurized by the pump, the incoming flow of liquids stops, and the high pressure check valves close. Next, the air line pressure to the air drive cylinder is dumped (to preclude

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further injection of LP into the chamber after a firing, with potentially hazardous results). Finally, the delay timer actuates the primer solenoid, which then fires the primer and initiates LP combustion in the chamber.

4.2 Transparent Injection Fixture

This type of fixture is particularly useful in exploring and assessing the nature and efficacy of the LP injection processes---especially in dynamically loaded systems using either liquid monopropellants or bipropellants.

The fixture constructed for use in this program is shown in Figure 7. This fixture was fabricated from optical quality polycarbonate. The chamber and injection geometry of the ignition test fixture was duplicated very closely in this transparent injection fixture. Wall surfaces in the transparent chamber were polished sufficiently to permit a good view of the chamber interior. Differences in injection phenomena arising from the use of a plastic surface rather than the metal surface of the ignition fixture are believed to be small and have been neglected here. The injectors (high-pressure check valves) used in the injection fixture, however, are the identical ones employed in the ignition fixture to avoid the known problems of performance sensitivity of injectors to small dimensional variations, scratches, surface finish differences, etc. For convenience, therefore, the transparent injection fixture can utilize the complete liquid propellant pumping system, most of the plumbing (except perhaps for a few short sections of tubing), and the same control system used with the ignition fixture for timing the injection.

This injection fixture operation duplicates that of the ignition fixture, except that a projectile and primer are not used, and the LP injected is not ignited.

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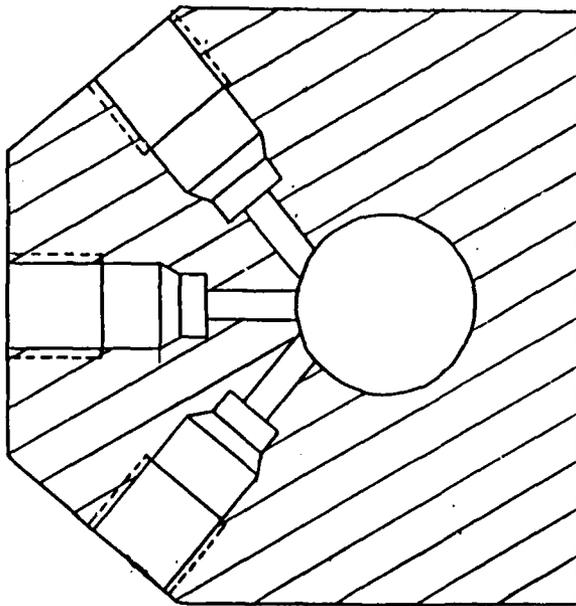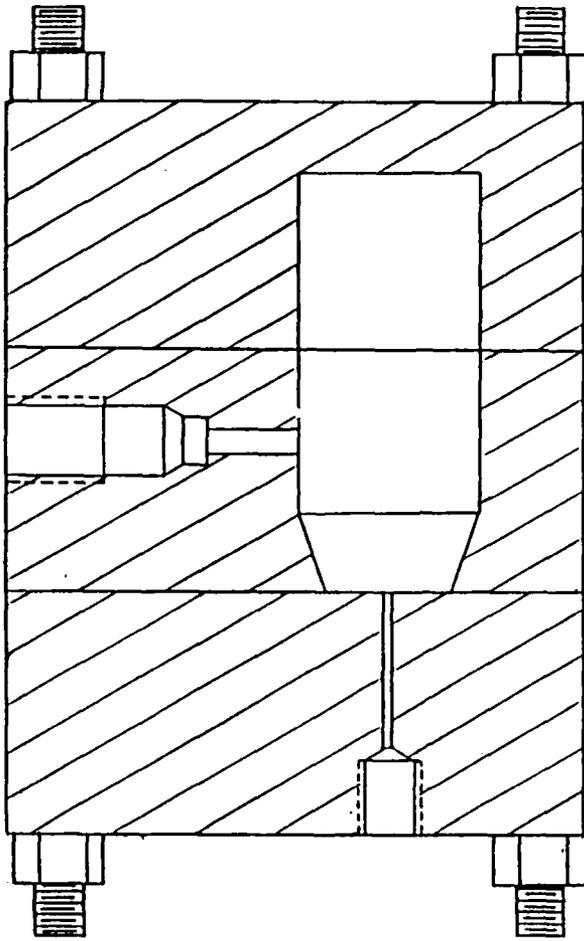
Figure 7. 25mm Transparent Injection Fixture

4.3 Range Facilities for LP Firings

Veritay Technology operates underground ballistic range facilities consisting of three test cells of approximately 3000 square feet each, one of which has been exclusively devoted to LPG testing for the past three years. As shown in Figure 8, each test cell is 50 ft x 60 ft with a height varying form 12 to 16 ft. Access to each cell is provided by conventional stairs, escape hatches and a 40-ft-long by 9-ft-wide elevator.

Each test cell is encased in reinforced concrete, has its own barricaded control room and its own ventilation system and escape routes, and is suitable for firing most small and medium caliber guns. All essential support facilities are located on site, including a basic machine shop for fabricating hardware and instrumentation used in experimental setups, an electronics shop, drafting facilities, and magazines for explosive and propellant storage.

Also available are four Nicolet digital recording oscilloscopes (16 channels) and two Hewlett-Packard 7090A plotters (6 additional digital channels), which are coupled to an IBM PC/XT computer for rapid digital data acquisition; closed circuit TV for remote viewing of tests; electronic equipment for calibrating sensors and taking necessary pressure, thermal, optical and timing measurements; and a single-frame film analyzer for evaluating high-speed motion picture photographic data.

On-site computing equipment available for use independently, or in support of range facilities operations, includes IBM PC/XT and PC/AT and Apple II microcomputers. A scanning electron microscope, Tukon hardness tester, gas chromatograph, and various combustion analyzing instruments are available through standing agreements with the State University of New York at Buffalo.

Figure 8

SUPPORTING FACILITIES AND EQUIPMENT

COMPUTING AND DATA ACQUISITION

On-site computing equipment includes IBM PC/XTs, Sperry ITs, an IBM AT, and Apple II microcomputers. Four Nicolet oscilloscopes (16 channels) and two HP 7090A plotters (6 additional channels are coupled to an IBM PC/XT for rapid digital data acquisition. Veritay also has access to a VAX through a standing agreement with the State University of New York at Buffalo.
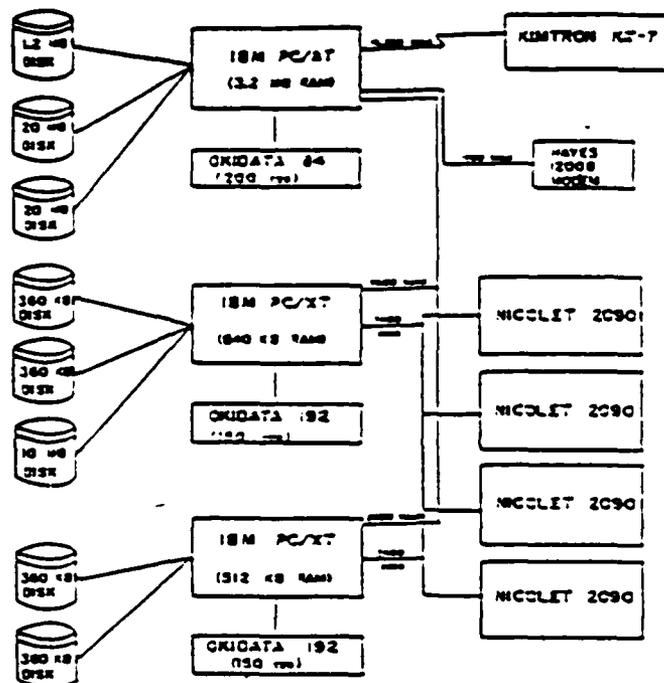
ELECTRONIC AND TEST EQUIPMENT

Experimental work is supported by a fully equipped electronics shop, closed circuit TV for remote viewing, a 16mm high-speed motion picture camera for motion analysis and a single-frame film analyzer for evaluating photographic data.

FABRICATION AND MACHINE SHOPS

Our fabrication shop is equipped for model making, ammunition handling, component assembly, propellant consolidation (30-ton press and solvent-control equipment), sensor fabrication, instrumentation and control electronics, and plastic vacuum forming. Equipment in our machine shop includes drill presses, bench grinders, milling machines, balances, a power punch press, lathes, and all essential tooling.

ISOLATED TEST CELLS
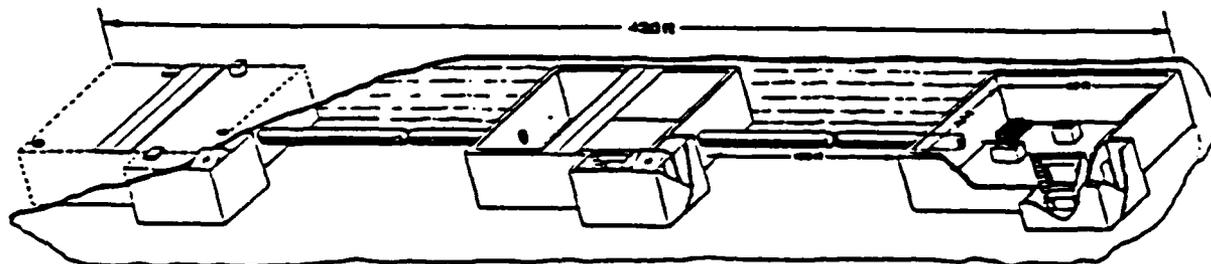
Veritay's underground test cells are suitable for firing most small and medium-caliber guns. The space is also ideal for programs requiring isolated testing, experimentation, or fabrication.

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Section 5.0

INSTRUMENTATION CONFIGURATION

5.1 General

One of the greatest needs in LP gun diagnostics is to arrive at a suitable set of instrumentation and diagnostic techniques which can be employed simultaneously and corroboratively to assess the key aspects required in achieving an understanding of the performance of guns. To the extent that such a set can be defined and can be practical for various LP gun systems, such a configuration may be considered as a baseline instrumentation system.

Several different types of instrumentation are briefly reviewed in the following subsections to indicate their basic features and potential uses in LPG diagnostics. These different kinds of instrumentation tend to complement one another, and by proper selection of a combination of sensors, a wide variety of diagnostic information can be obtained. In past efforts, we have learned that results from one sensor or from a single diagnostic technique seldom provides a complete picture. When several measurements are taken together, however, the picture becomes clearer and the level of understanding improves.

Emphasis in the current investigation has been placed on developing such a combination of sensors and techniques suitable for visualizing selected internal LP phenomena and evaluating their associated parameters quantitatively. Particular attention has been given to the exploration of photographic techniques for improved visualization, and to the simultaneous use of pressure and thermal sensors to obtain quantitative parameter measures.

5.2 Pressure Transducers

Piezoelectric pressure transducers are typically the only known types which cover an adequate pressure range, are sufficiently rugged, and have a fast enough response to be useful for routine ballistic testing. At Veritay such transducers manufactured by PCB Piezotronics, Inc., of Buffalo, New York, are commonly used. These transducers can measure pressures up to 120,000 psi (827 MPa). The 119A series is acceleration compensated and has a frequency response of 500 KHZ. Factory supplied calibrations are typically used and are claimed to give values accurate within three (3) percent. Independent calibrations made at Veritay using a model 55-150 dead weight pressure tester manufactured by Chandler Engineering, Co., of Tulsa, Oklahoma, generally confirm the factory supplied values and the claimed accuracies.

A number of pressure transducer ports were located in the 25 mm LP ignition fixture noted previously in Figure 1. The locations of these ports are given below in terms of general position and azimuth angle, measured clockwise in a vertical plane perpendicular to the bore axis (as seen from the breech looking toward the muzzle) from the top (= 0 degrees):

Location	No. of Ports	Azimuth/Use (interchangeable)
Breech End	1	270 degrees - pressure
Chamber Window	2	22 degrees - pressure 338 degrees - temp.
Barrel Window	2	270 degrees - pressure 315 degrees - temp.
Barrel Extension	2	315 degrees - pressure 135 degrees - temp.

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Front and back transducers in the chamber are available to confirm and assess hydrodynamic wave effects in the chamber. Provision is made to position an additional transducer with the same 270-degree azimuth as the port at the breech end by mounting this new transducer in a steel chamber window plug. This arrangement can allow comparison of pressure wave measurements along the same azimuth from the breech to the barrel window region. By rebuilding the seal on the barrel extension, one of the transducer ports in the barrel could also be brought into this same azimuthal alignment for pressure comparisons.

Further, comparision of the dynamic characteristics of the pressure histories obtained with multiple pressure transducers at the same axial position will indicate via phase shifts whether or not the combustion process within the chamber (or barrel) is symmetric.

The ability to mount transducers in the steel window plugs give a further option of using blind transducers. These are transducers installed in the ignition test fixture without a port leading directly to the chamber. Such transducers will be sensitive to the vibrational pickup of the other "non-blind" transducers, but will not record the fluid pressure. A blind transducer located adjacent to an active one can provide the necessary information to separate the high-frequency data that originates in the chamber wall from the frequencies that exist in the fluid. Even though these pressure transducers are acceleration compensated, severe vibrations can cause a transducer to generate a signal.

5.3 Thermal Sensors

Surface thermocouple sensors are being used routinely in gun and ammunition research at Veritay to indicate short-

duration heating of surfaces. These sensors are rugged and have very rapid response characteristics, both useful features in LPG phenomenology investigations. The design of a typical surface thermocouple sensor that was fabricated and used in the current program is shown in Figure 9. This sensor is configured to mount in a pressure transducer port and maintain a setback from the wall surface of about 0.003 inches (0.08mm). This setback prevents a passing projectile from contacting the sensor surface when the transducer is mounted adjacent to the bore of a barrel.

The central element of the thermocouple is a 0.014-inch (0.356mm) diameter nickel wire with an insulating nickel-oxide coating. This is crimped into the nose section of the body. The body, in turn, serves as the second material of the thermocouple, and, typically, is chosen to be identical to the barrel material to obtain a good match between thermal properties of the sensor and the barrel. The material used here for the body is AISI 4140 steel. The thermocouple junction is formed by plastically deforming the uppermost layer of the central wire in mushroom fashion perpendicular to the wire axis, so the wire contacts the surrounding cylindrical nose section of the upper surface. This material combination, of course, requires a separate calibration to be made for the combination to be used as a thermocouple.

A preliminary calibration using the ice and boiling points of water is shown in Figure 10. For comparison, an ANSI Type K (chromel-alumel) thermocouple was also measured and compared with standard calibration values in Figure 10. The use of an additional primary standard point for calibration, the boiling point of sulfur at 832.3 degrees F (444.6 degrees C) was attempted with both types of thermocouples, but our technique was not sufficiently refined to obtain useful results. For present purposes, the two-point calibration is adequate; it needs further attention and the benefit of another calibration point for future work.

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THERMOCOUPLE WIRE

BACKING BOLT

SENSOR BODY
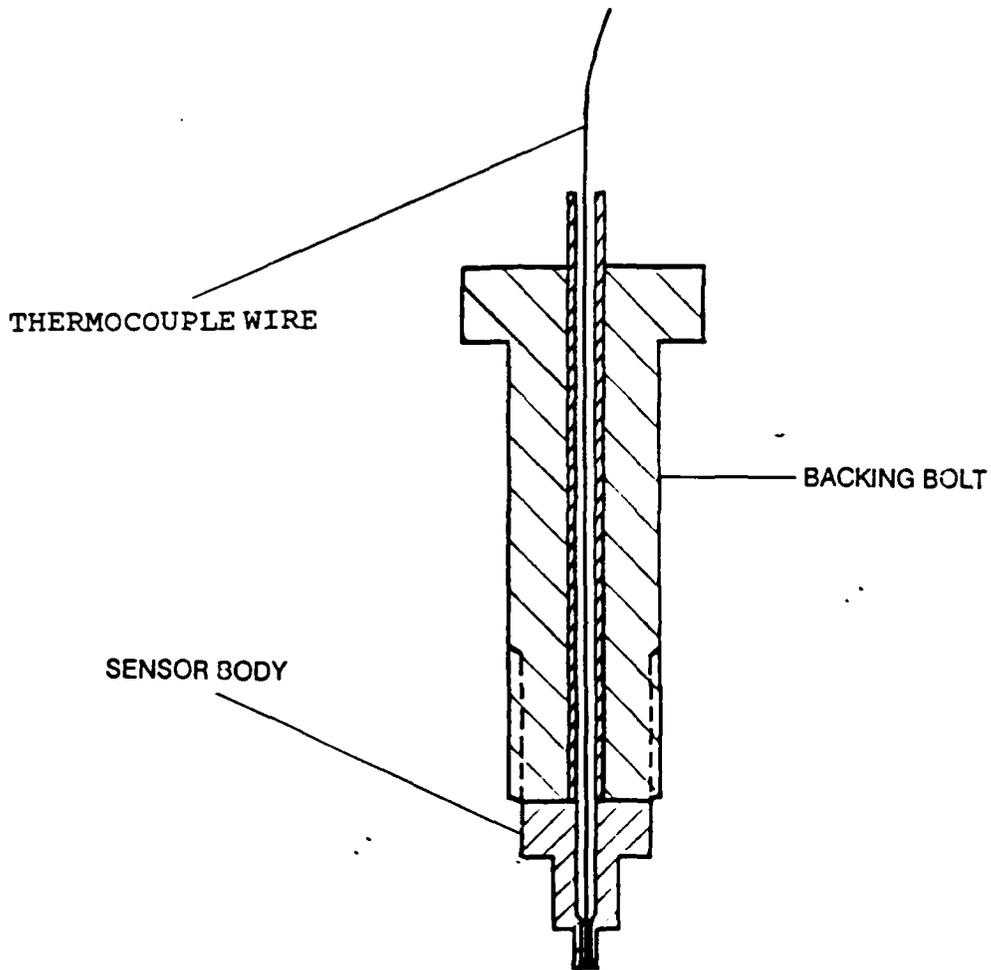
Figure 9. Typical Surface Thermocouple Sensor
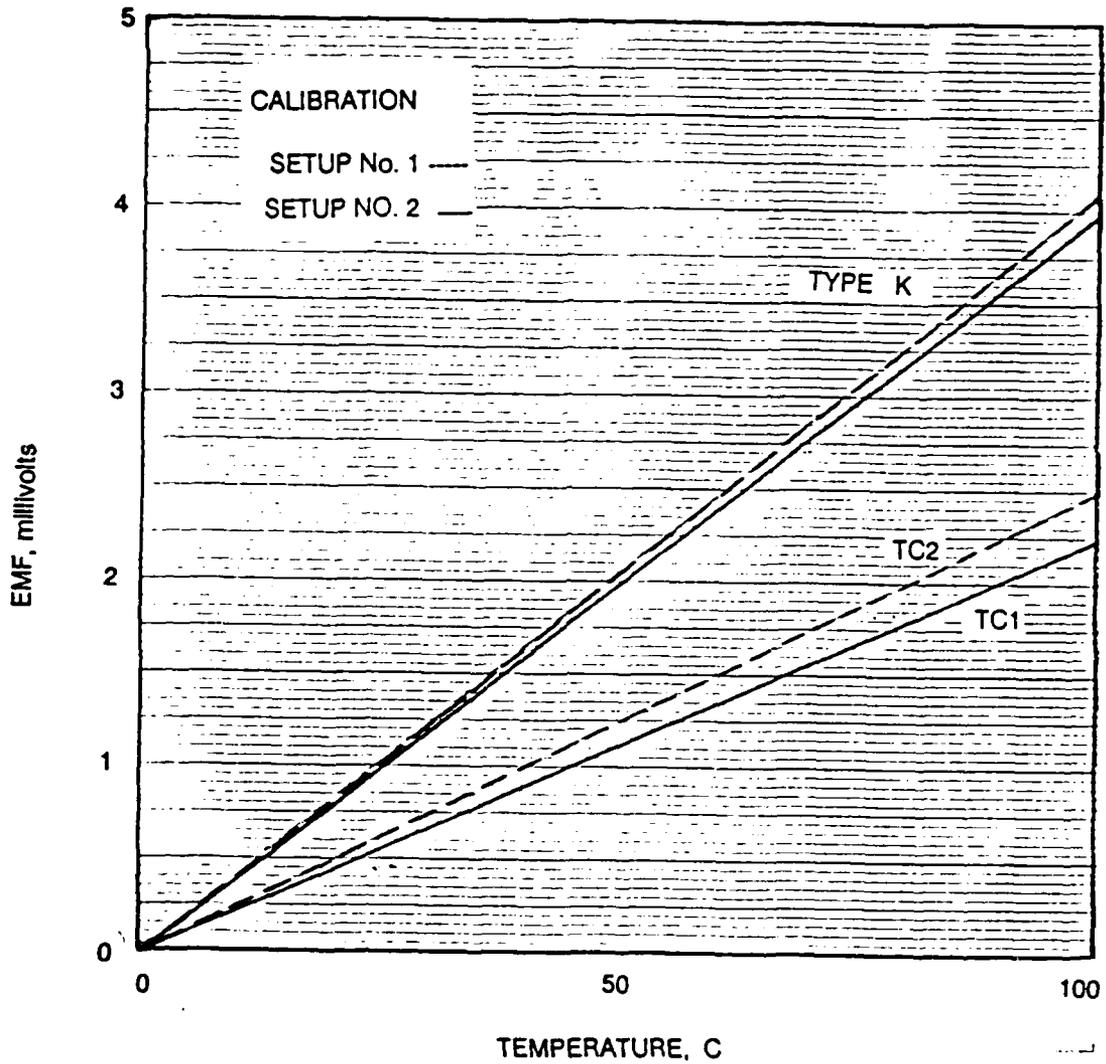
Figure 10. Surface Thermocouple Preliminary Calibration

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5.4 Pressure Resistant Windows

Three high-pressure-resistant window ports are provided
in the LP ignition fixture; two diametrically opposed ports in
the forward position of the chamber, and one in the barrel
centered 2.75 inches (69.85mm) ahead of the chamber. A sapphire
window, together with an acrylic plug with an inner cylindrical
contour matched to the diameter of the chamber or bore, was
fitted to each port, as shown in Figure 11. The contoured plugs
distort the optical magnifications of the chamber interior as
viewed through the windows, but their use is believed to be
warranted since these plugs avoid introducing abnormal liquid
flows and turbulence as well as combustion perturbations that
might otherwise occur with the use of flat-faced plugs.

An acrylic plane-convex cylindrical lens was configured
for each port to correct the paraxial magnification distortion
introduced by the cylindrical surface of the inner acrylic plug.

5.5 High-Speed Photography

5.5.1 High-Speed Framing

Veritay owns a HYCAM 16mm camera with f/3.3 zoom lens, which
is a rotating-prism-type instrument suitable for taking high-
speed motion pictures of LPG phenomena. The camera has both 100
ft (30.5 m) and 400 ft (122 m) reel capabilities. The basic
camera can take picutes at a framing rate of 11,000 pps when
using a full-frame prism. When half or quarter frame prisms are
used, the maximum framing rate increases to 22,000 or 44,000 pps,
respectively. Veritay owns a full-frame prism and had a
Government-owned, half-frame prism available via another Army
contract for use on this program. Resolution with a half-
frame prism is claimed to be a least 35 line pairs per
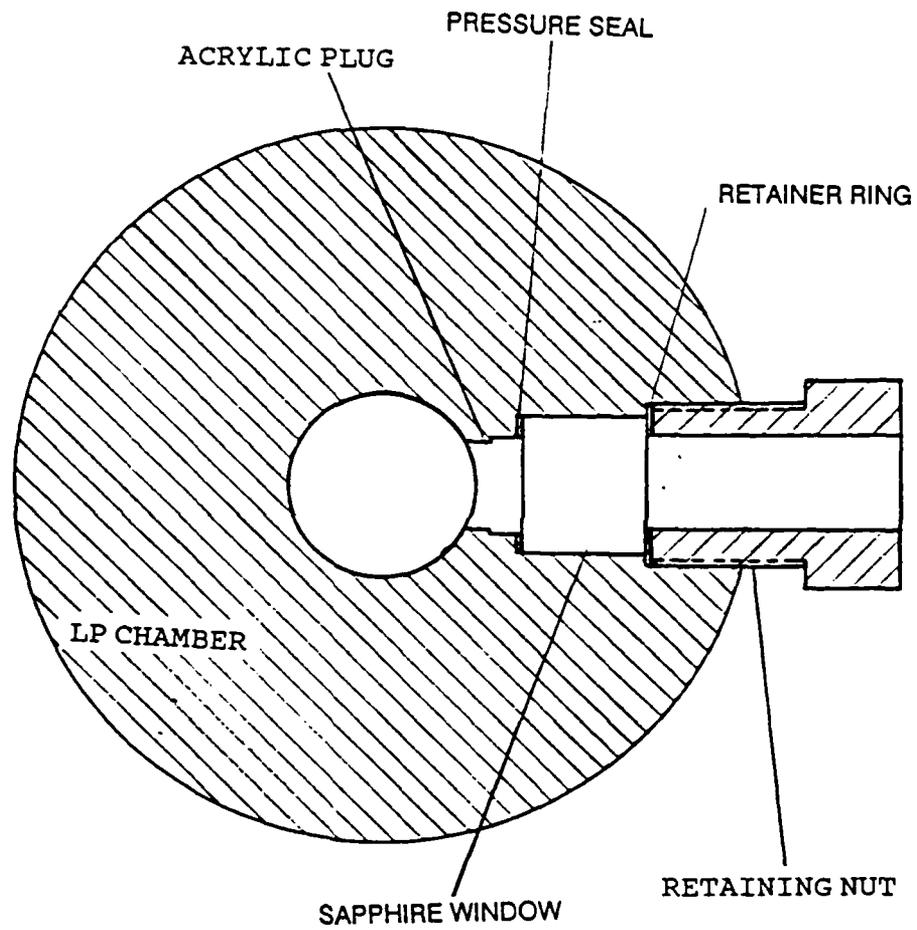
Figure 11.   Window Mounting Detail

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millimeter, and 20 line pairs per millemeter with a quarter-frame prism.

Realistic framing rate values for 100-ft. reels with a half-frame prism are about 15,000 pps after a film travel distance of about 75 feet (22.9 m). The time between frames at this speed is about 66.7 microseconds, and the exposure time per frame (the rotating prism sweeps the image in the direction of film motion) is 26.7 microseconds per frame.

Corresponding values for 400-ft. reels with a half-frame prism are about 22,000 pps after a film travel of about 300 ft. (91.5 m). At this speed, the time between frames is about 45.5 microseconds and the exposure time per frame is about 18.2 microseconds per frame.

While these frame separation and exposure times may appear to be relatively short, they are actually rather long for ballistic events. Doubling the rates, or halving the time, by using a quarter-frame prism does not shorten the time sufficiently to be of significantly greater value; on the negative side, the field of view is simultaneously cut in half by using such a prism.

In the face of these weaknesses, past experience has shown that when photographing combustion events using illumination provided by the combustion event itself, the exposure times indicated are realistic to achieve useful photographs. This framing camera was thus used to further explore its utility in assessing LPG phenomena.

We also sought to obtain improved time resolution -- especially for exposure, since image motion during a long exposure results in a blurred image. Our approach in this endeavor was to use a variant of streak photography.

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5.5.2 Space-Time-Shared Streak Photography

The HYCAM 16mm camera noted previously is also adaptable to streak photography. The streak attachment supplied by the camera manufacturer was modified by removing the adjustable slit, since our objective was to place such a limiting field stop at the object, rather than in the film plane. The latter approach facilitated camera setup, focusing, etc.

In conventional streak photography, a long narrow slit is placed lengthwise along an object or chamber to be examined. The slit and camera are oriented so the length of the slit is perpendicular to the direction of film travel. An object that changes position along the slit as a function of time will then be photographed through an open shutter camera as a streak on the film. This streak tracks across the film as well as down the length of the film as shown in Figure 12. For convenience, it is customary to consider a position along the slit by a distance x, measured from one end of the slit. The position along the film is, of course, time t, measured with respect to some convenient origin. Conventional streak photography, therefore, characterizes the linear position -- time history of objects which appear in the slit.

If one is willing to forego a completely continuous record of x versus t, as provided by conventional streak photography, and accept a space-time shared data record, then a variant of streak photography allows one to obtain time history information in two directions x and y at right angles to each other. While this scheme may not be universally applicable, it appears to hold some promise for use in LP gun diagnostics.

This time shared scheme utilizes a mask with openings distributed in a selected two-dimensional pattern, rather than a single slit. Such a mask is shown schematically in Figure 13.

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COVERED WINDOW

OPEN SLIT

POSITION, x

TIME, t
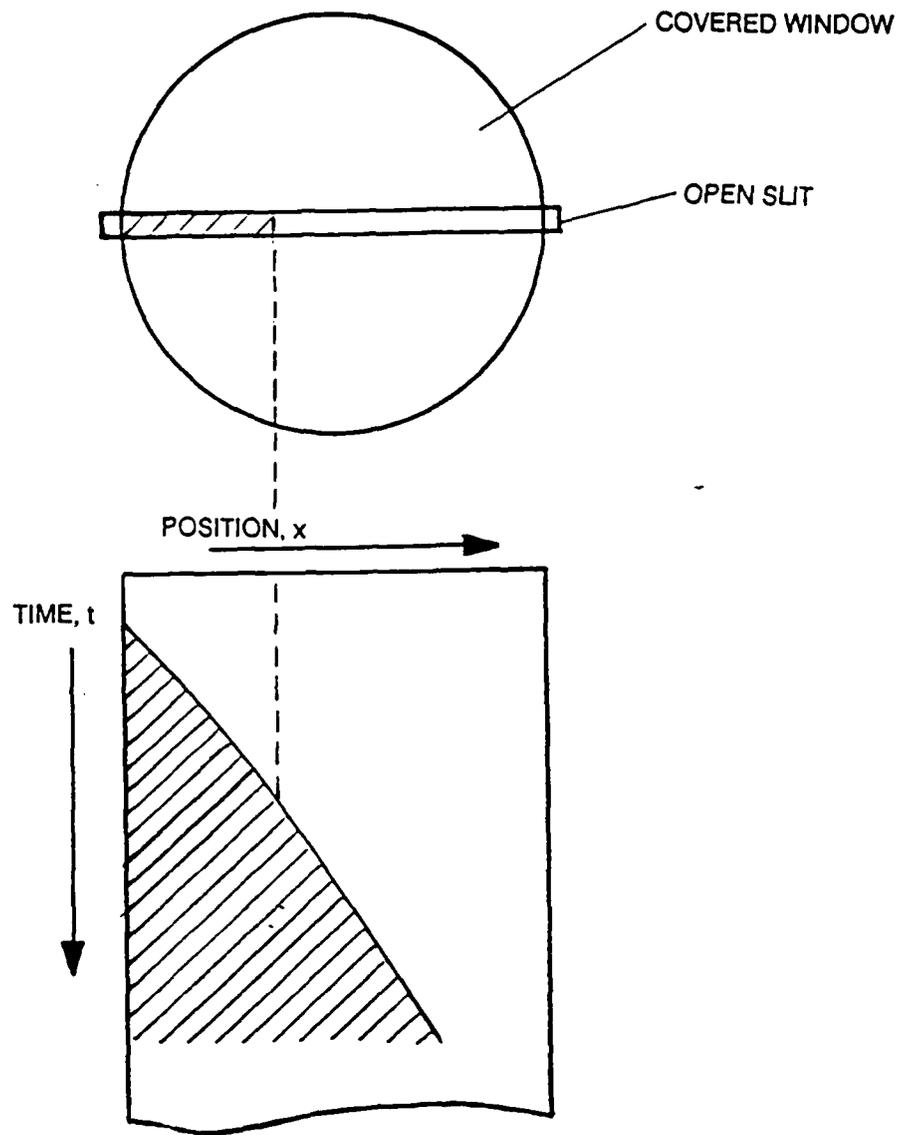
Figure 12.   Conventional Streak Photography
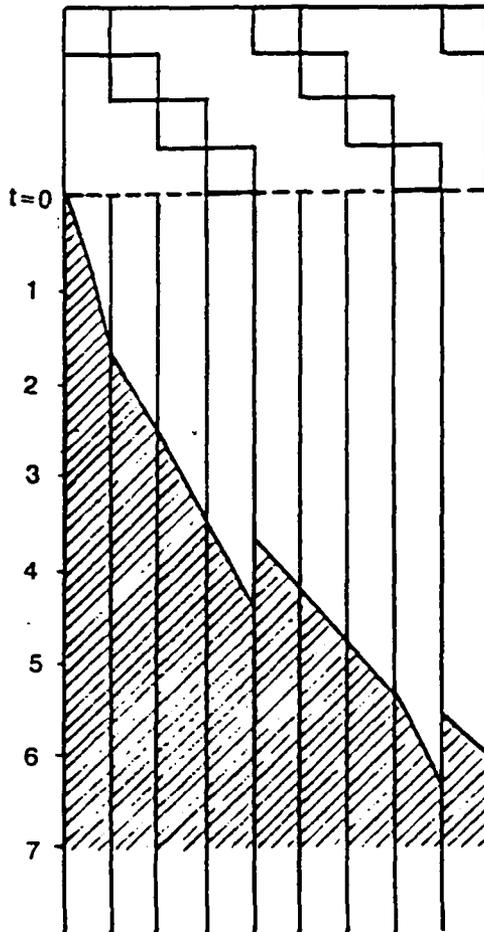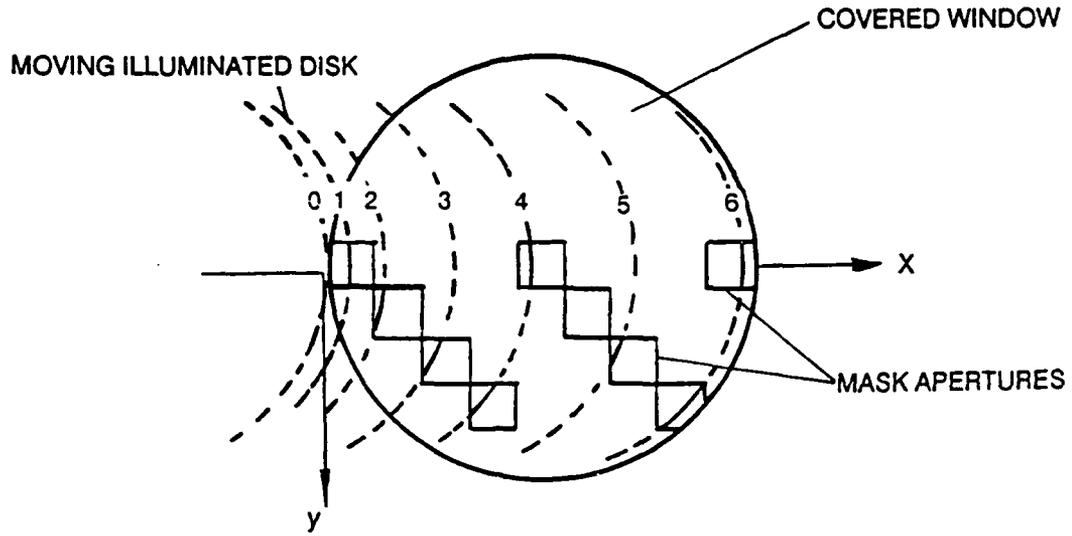
Figure 13. Space-Time Shared Streak Photography

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The pattern of openings on this mask was selected to examine the history of an extended illuminated object moving in the x direction. For simplicity, suppose the object is a uniformly illuminated circular disk as shown. Let the center of the illuminated circular center pass exactly along the x-axis through the center of the mask, so there is symmetry about the x-axis; then only the bottom half of the mask needs to be examined.

The mask will be imaged on the film, as shown, at time zero. As time passes, the illuminated disk will show through the mask and form the streak pattern shown. A curve can be passed through the beginnings of the streak lines which all correspond to apertures with the same y value. A separate curve can be drawn for each successive y value.

Conversely, given these separate curves, the passage of the front edge of the illuminated disk behind the mask can be reconstructed.

With some development of the technique, including the selection of a useful mask pattern, it should be possible to retrieve the shapes of self-luminous combustion wave fronts that pass behind the mask.

The time resolution of this technique is as good as the resolution of images along the film. While extremely short-time resolution is probably not possible, it sems likely that time resolutions of around three to five microseconds should be readily achievable. This would represent a significant improvement (by a factor of about six) over the 18 to 27 microsecond resolution, which is obtained when the camera operates in the framing mode with a half-frame prism.

5.6 Computer-Controlled Firing and Instrumentation

The LPG system operation involves various steps of sequencing and monitoring of mechanical and electrical components, both of which are considered critical from the standpoint of data aquisition, system control, and reproducibility. Since a typical LPG firing event occurs within a one-second time interval, manual system operation is impractical. Therefore, a need exists for a system controller, that not only incorporates both programmability of time delays and device sequencing, but also stands vigil to make split-second decisions, such as an "abort" in case of an LPG malfunction.

To fulfil this task, an Apple II microcomputer was adapted in the LPG system design (as shown in Figure 14, "LPG Computer System Block Diagram"). Its abilities include, but are not limited to, all of the above-mentioned features.

Timing for the system sequencing is achieved via a real-time clock board, separate from the microprocessor oscillator. An I/O control module, separate from the computer peripherals, handles A/D and D/A conversion as well as providing buffered outputs to power controllers used for air actuators, a high-speed camera, primer initiator supply, etc. Also, a special voltage offset design is added to perform a "tare" on the line pressure transducer to ensure correct threshold detection over transducer "creep."

The LPG Computer Program (VER 3.1H) incorporates all the necessary data used for creating sequences, time delays and threshold measurements. Parameters may be changed by the user, by entering new values in place of the default values. These values will then become the new default values, and remain so throughout program operations until changed again. When the LPG system is ready to be tested, the user must "step" through the

Figure 14. LPG Computer System Block Diagram

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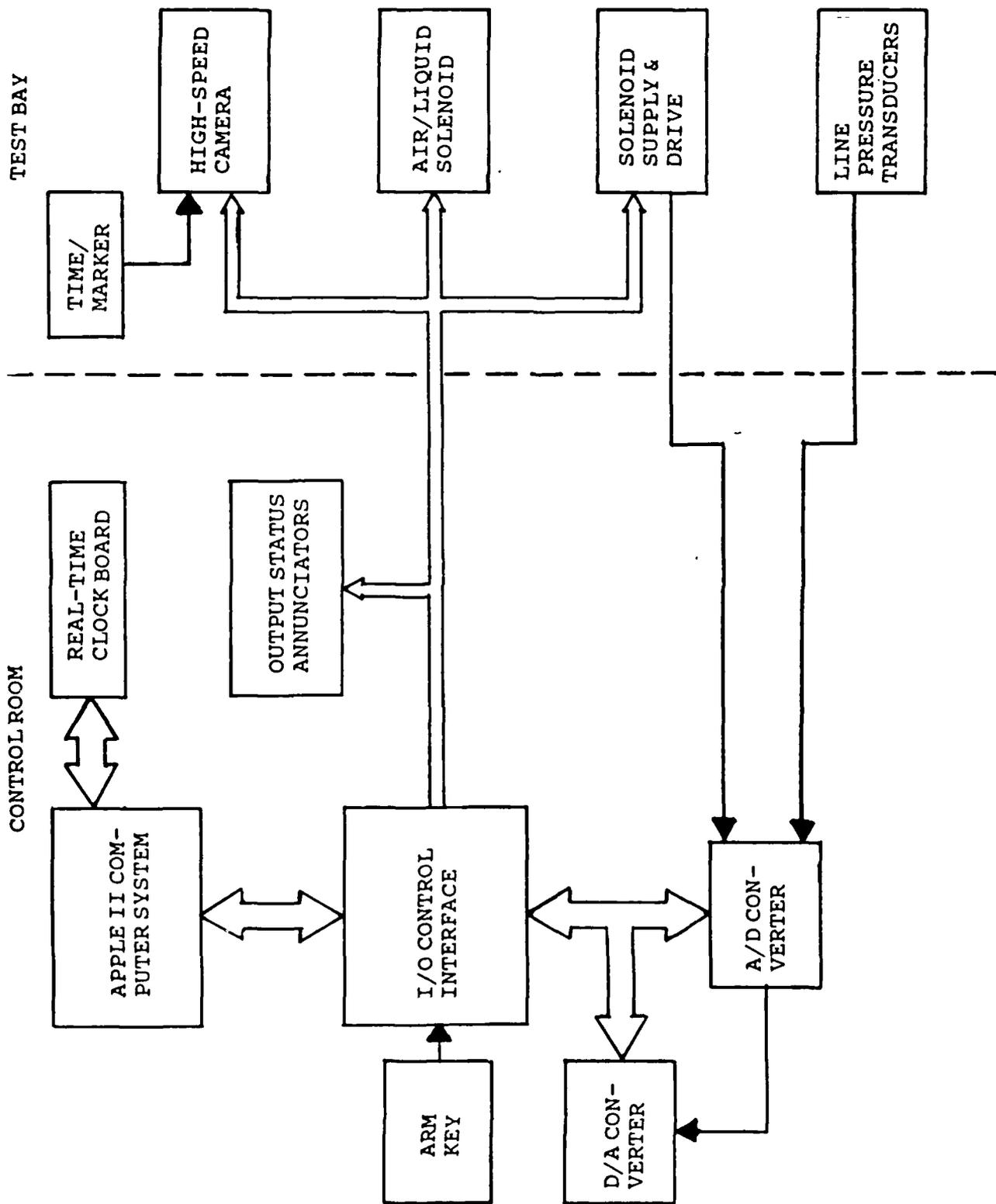
program's series of prompts as displayed on a computer monitor.
Once the user has committed the system to "Commence Injection,"
the computer takes control and safely injects and initiates the
LPG. After the LPG system has "fired," the computer prompts the
user to reset and disarm all mechanisms pertaining to its
operation. The preset definitions and default ranges currently
employed are shown in Table 2 and correspond to key injection
events indicated in Figure 15.

Table 2
PRESET DEFINTIONS AND DEFAULT RANGES

o   Air-to-liquid Inject Delay: (0 to 2.55 sec);
     Delay between "air supply on" to start of liquid
     injection

o   Hycam: High-speed camera delay (optional) (-2.55 to 2.55
     sec); synchronizes film with event

o   Liquid Inject Inhibit: (0 to 2.55 sec); Prevents
     premature injection between injection start and line
     pressure threshold

o   Air Dump Delay: (0 to 2.55 sec); Time between
     line pressure established and air supply dumped

o   Fire Delay: (0 to 2.55 sec); Time between line pressure
     established and primer initiation (always less than air-dump
     delay

o   Line Threshold: (0 to 2.55 sec); Voltage ouput of line
     transducer at which fire delay time is referenced

In the event of system leaks or an error in injection
timing, the computer will detect the abnormality and cause a
system abort, returning all operations to a reset and safe
(disarmed) condition. The program then displays the cause of the
abort condition on computer monitor so that correct action may be
taken to remedy the situation, thereby reducing the "downtime."

A - LIQUID INJECTION BEGINS
B - INJECTION PRESSURE THRESHOLD
C - LINE PRESSURE DUMPED
D - PRIMER IGNITION
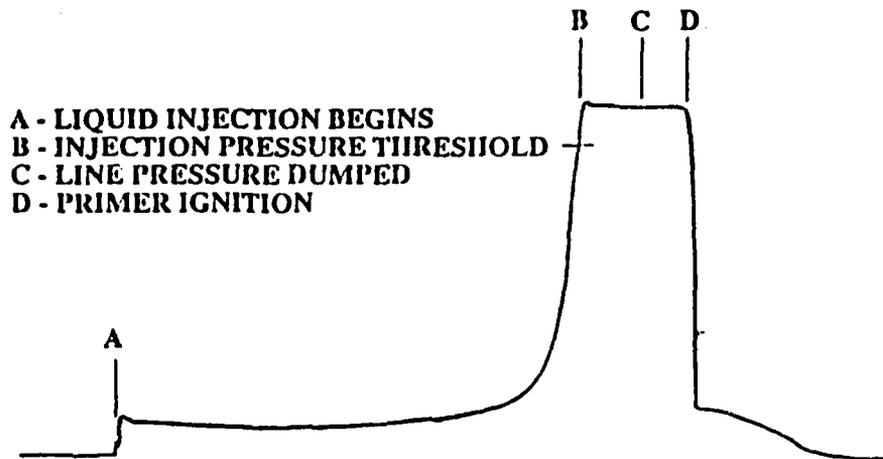
Figure 15.   LPG Computer Injection/Ignition Sequence

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Section 6.0
TEST RESULTS

The instrumentation feasibility testing included both
shakedown and full ballistic tests with the complete LP injection
fixture, as indicated in the outline of program tasks in
Section 2.0, "Investigative Program." In addition, tests were
conducted with the transparent injection fixture to examine the
nature and efficacy of the LP injection process. In both cases,
the systems were dynamically loaded with a bipropellant.

Full operating safety procedures for propellant
handling and test firings in LP gun systems were employed for all
tests in which one or both of the bipropellant components were
injected into a fixture---whether or not an igniter was used.
The latter case was included to avoid potential hazards which
could arise either from adiabatic ignition at the end of the
injection cycle, or from LP leaks or structural failures in
fixtures. Direct visual observation of the tests was thereby
precluded; overall observation of system functioning was possible
by closed circuit TV monitors, but observations for data purposes
were made photographically.

Injection tests were initially conducted in the
transparent fixtures to assess the following dependent
parameters/phenomena:

o   Fuel droplet dispersion history (qualitative)

o   Dispersion of ullage air into small bubbles, and

o   Time interval suitable for LP firing when droplets
     and bubbles are most homogeneous. (This interval
     is needed to determine the delay time from
     completion of injection until firing).

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Operating-type independent injection parameters included:

o   LP injection time,

o   LP injection (final) pressure.

The hydrocarbon fuel used in the bipropellant injection tests was colored with BASF Sudan Black organic soluble dye to enhance the fuel contrast with the 70 percent hydrogen peroxide oxidizer.

Selected injection tests were conducted as indicated above to establish suitable conditions for operating the LP ignition fixture for test firings. These test results showed that adequate fuel droplet and ullage air bubble homogeneity, as well as fuel droplet sizes, could be obtained using an LP injection (final) pressure of approximately 1,100 psi (7.59 MPa), an injection time of 1.0 second and a delay time of about 0.25 second.

An oxidizer-to-fuel volume ratio of about 11:1 and an igniter booster charge of 4.63 grains (0.30 grams) Hercules Bullseye smokeless powder were selected on the basis of past testing experience with a similar bipropellant.

Two initial shakedown firing tests of the 25mm LP ignition fixture with steel plugs in the window ports were conducted using the above ignition conditions. Test No. 1 was fired using a chamber load of oxidizer alone. This condition was used to confirm the approximate suitability of primer coupling, and in this test resulted in a peak pressure of 17.2 kpsi (118 MPa). Data from test No. 1 were lost because of a procedural error. The pressure time results of shakedown test No. 2 are shown in Figure 16. The pressure spike early in this curve reached 35.5 kpsi (245 MPa), a value which the fixture and

45

PRESSURE
(5000 psi/div)

PRESSURE
(50 MPa/div)
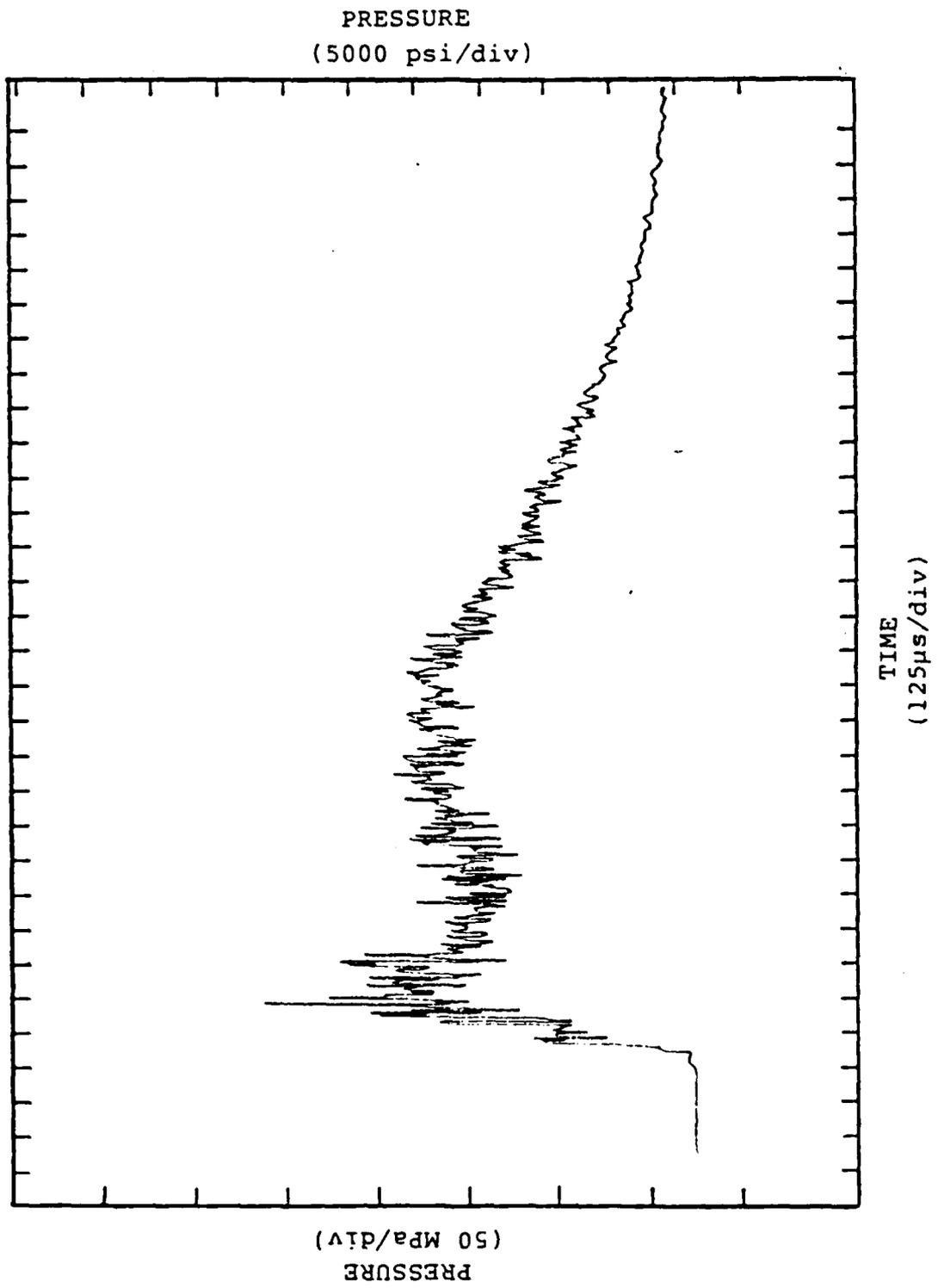
TIME
(125μs/div)

Figure 16   Pressure-Time Results of Shakedown Test No. 2

sapphire windows could withstand. The pressure spike was lowered on all succeeding test firings by reducing the booster charges to 3.86 grains (0.25 grams) of Bullseye.

Test Nos. 3 through 5 were repetitions; they were all conducted using this reduced booster charge to examine reproducibility of pressure-time results in the new 25mm LP ignition fixture. Unfiltered test data taken with a pressure transducer located near the breech of the chamber for each test are shown in Figure 17. These pressure curves are quite similar to one another. They indicate qualitatively that an adequate level of reproducibility and a suitable set of conditions have been attained to proceed with firing tests in the ignition fixture without taking undue risks of causing hardware failure, and especially of breaking the sapphire windows. In this first test series, data were also taken with another pressure transducer located near the forward end of the chamber. Generally, the pressure-time results from the front and rear of the chamber agreed closely, except the traces taken at the front indicated a little more high frequency noise.

During the remainder of the tests pressure transducers were employed at all four locations indicated earlier in Section 5.2, "Pressure Transducers," i.e., at the breech and window positions in the chamber, at the window position in the barrel, and near the muzzle of the barrel extension.

Particularly interesting results were found in tests Nos. 9 through 12, and 15, 18 and 19. Sample pressure-time curves for three of the four transducers used in tests 15, 18 and 19 are shown in Figures 18, Figure 19 and Figure 20, respectively. In these figures, barrel position 1 (and the barrel window) is centered 3.00 inches (76.2mm) ahead of the chamber toward the muzzle, and barrel position 2 is located 7.19 inches (182.6mm) further toward the muzzle than position 1. (For

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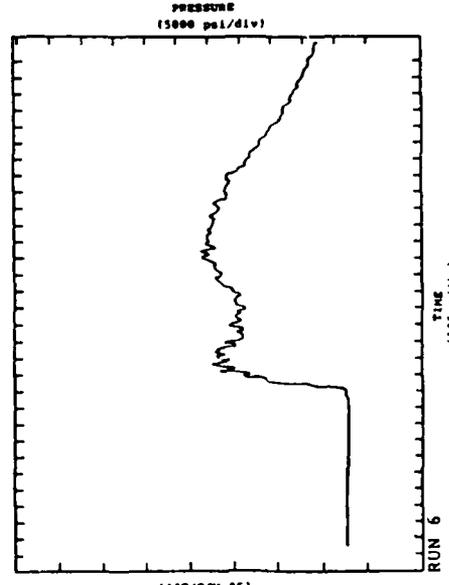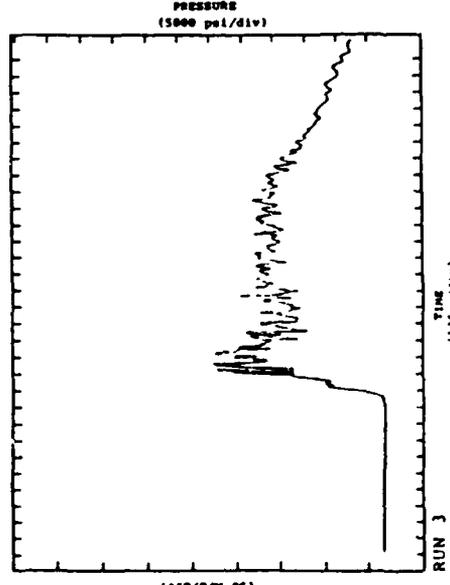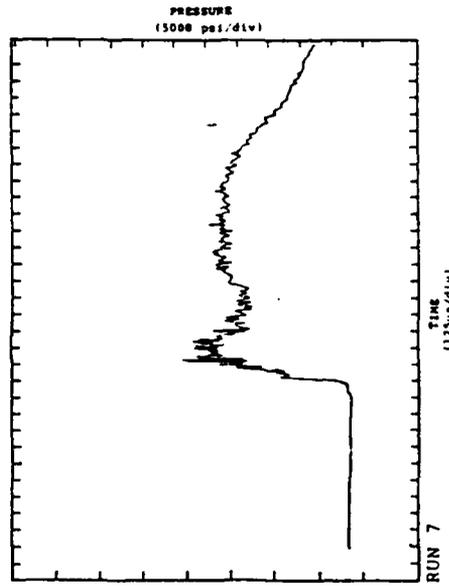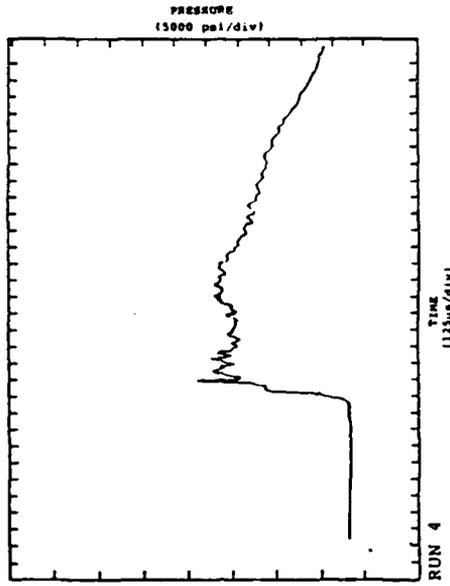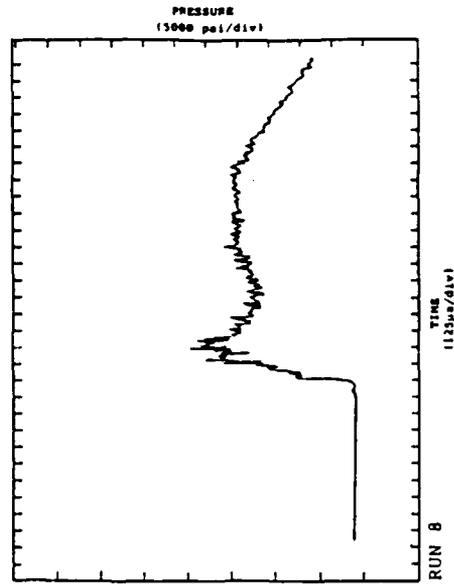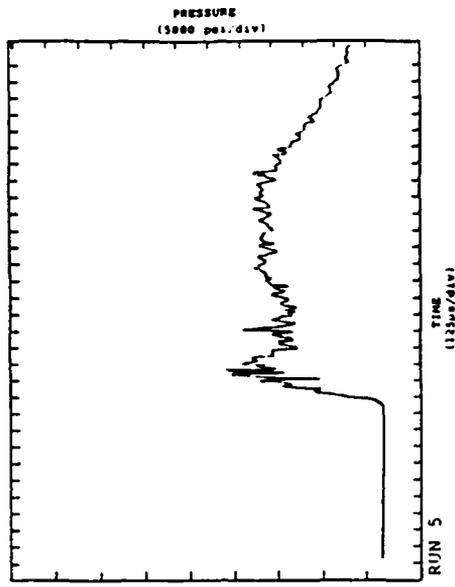
Figure 17. Pressure-Time-Reproducibility Results For 25mm LP Ignition Fixture

PRESSURE
(5000 psi/div)

PRESSURE
(50 MPa/div)

TIME
(125μs/div)
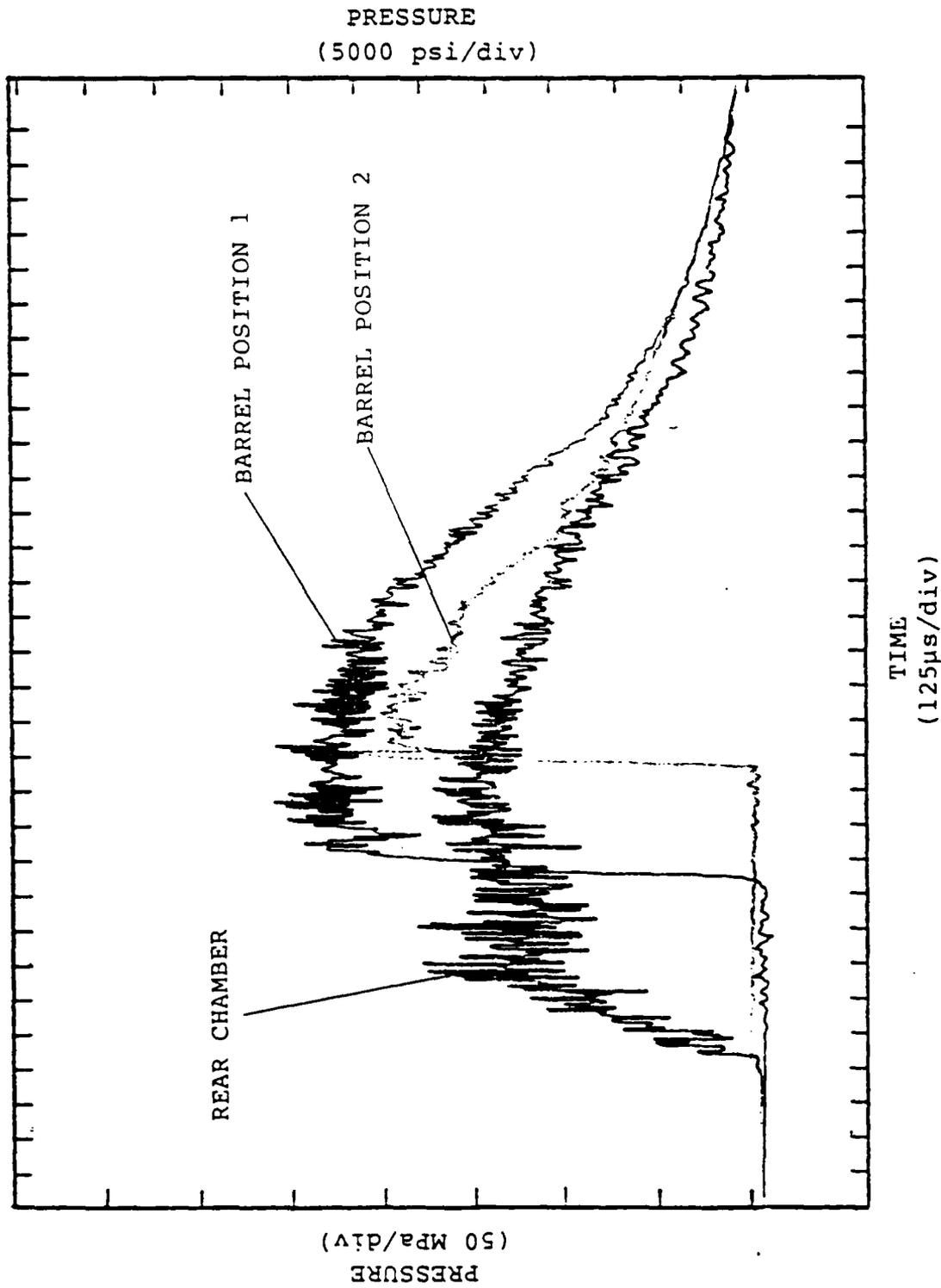
Figure 18. Chamber-Barrel Pressure Results For Test No. 15

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PRESSURE
(5000 psi/div)

PRESSURE
(50 MPa/div)

TIME
(125μs/div)
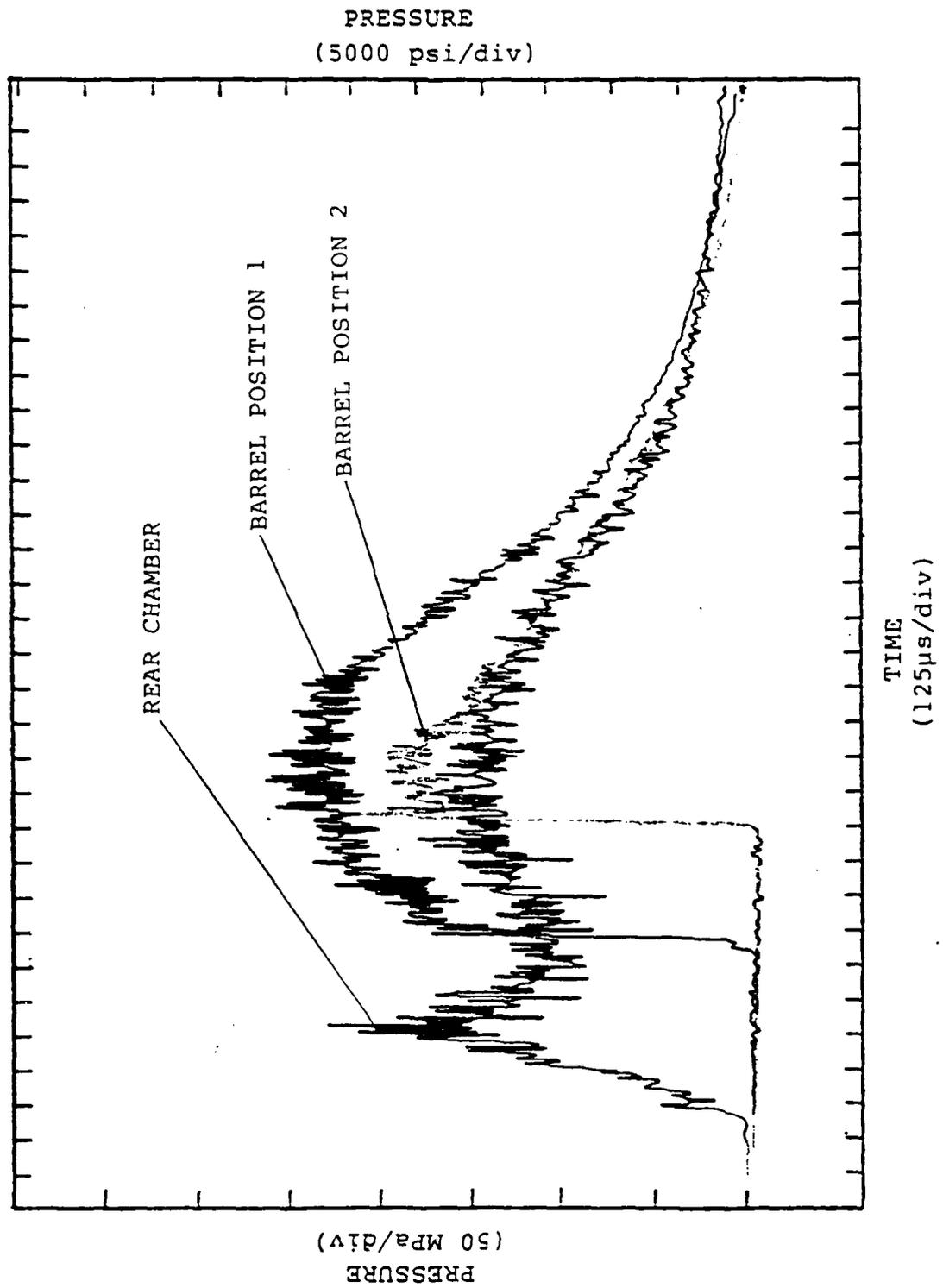
Figure 19. Chamber-Barrel Pressure Results For Test No. 18

50

PRESSURE
(5000 psi/div)
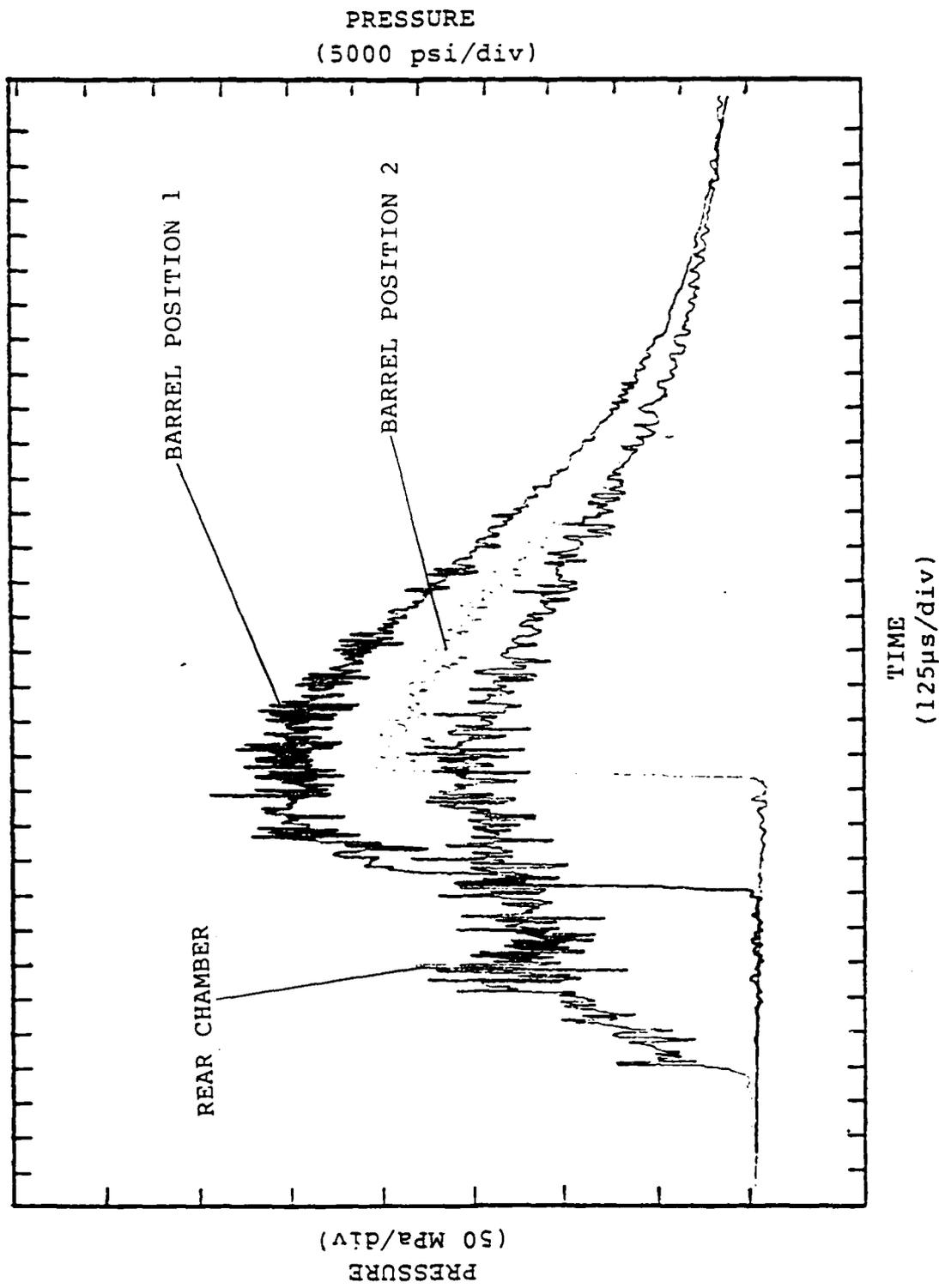
Figure 20. Chamber-Barrel Pressure Results For Test No. 19

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completeness, the front chamber window and transducer port centers are located 0.625 inches (15.9mm) toward the breech from the chamber front, and the rear chamber position is 1.656 inches (42.1mm) further toward the breech than the chamber window).

The curves in Figure 18 indicate a rather normal pressure behavior at the rear chamber transducer location. This also occurred at the chamber window position, but that pressure curve is not shown for overall clarity. As the projectile moved down the barrel and cleared position 1, the transducer at that location recorded a significant pressure increase to a value which was about 12 kpsi (82.8 MPa) greater than the pressure at the rear of the chamber at that time.

A similar pressure increase of about 6 kpsi (41.4 MPa) occurred just after the projectile cleared barrel position 2. Collectively, these pressure excursions imply the existence of a traveling charge phenomena behind the projectile. The pressure increment observed seems to decay as the projectile moves farther down the barrel, as would likely be expected in a traveling charge case. The pressure curves in Figures 19 and 20 show analogous results for test nos. 18 and 19, respectively.

When this type of behavior was first observed in Test No. 9 the barrel transducers results were suspect. The barrel transducers were removed, recalibrated, and found to be in satisfactory working order. They were even fired in another small arms test fixture in parallel with other transducers. This further verified the proper operation of the transducers used in Test No. 9. Subsequent tests under this program have shown that the pressure excursion phenomena is quite reproducible.

As a further check on the traveling charge phenomena, and the continued pursual of the task to incorporate and use surface thermocouple sensors for diagnostics, two such sensors

were installed at positions 1 and 2. These were designated TC1 and TC2, respectively. Operational problems developed during tests with the sensor TC2 mounted in barrel position 2. The other, TC1, performed satisfactorily.

Simultaneous pressure and bore surface temperature results are shown in Figure 21 for test No. 18, and in Figure 22 for test No. 19. In these figures it is apparent that the time response of the surface thermocouple is quite rapid, even though its actual value is currently unknown. From the near simultaneous rise of the temperature curve with that of the pressure at barrel position 1, any time delay in temperature response is less than about 25 microseconds.

This short delay further indicates that no liquid propellant film of significant thickness is apt to be covering the surface of the thermocouple, because if so, a greater time delay in rise of the temperature curve would be expected. The corroboration of pressure and temperature findings in this case further supports the view that the phenomena under observation here is probably a traveling charge phenomena.

The potential utility of high-speed photography in assessing phenomena associated with injection and combustion in LP gun operation was also explored.

In test Nos. 7 through 12, and test No. 15 the HYCAM 16mm camera was used with 100 ft. film reels in the half-frame, high-speed framing mode. The film used was Eastman Kodak type 7250, with a speed rating of ASA400 for tungsten with a color temperature of 3200 degrees K. For framing, the camera was equipped with an f/2.8, 20-60mm zoom lens made by Pancinor. The camera was used with f/4 as the lowest aperture stop number, even though the camera itself will accommodate an f/3.3 setting. We understand that lower f/number lens settings give unwanted

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PRESSURE – BARREL POSITION 1

TEMPERATURE – BARREL POSITION 1

PRESSURE – REAR CHAMBER
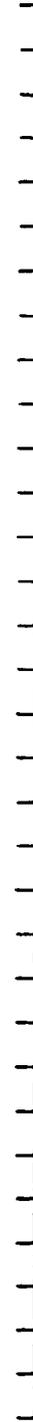
Figure 21. Simultaneous Pressure-Temperature Results For Test No. 18

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PRESSURE - BARREL POSITION 1

TEMPERATURE - BARREL POSITION 1

PRESSURE - REAR CHAMBER
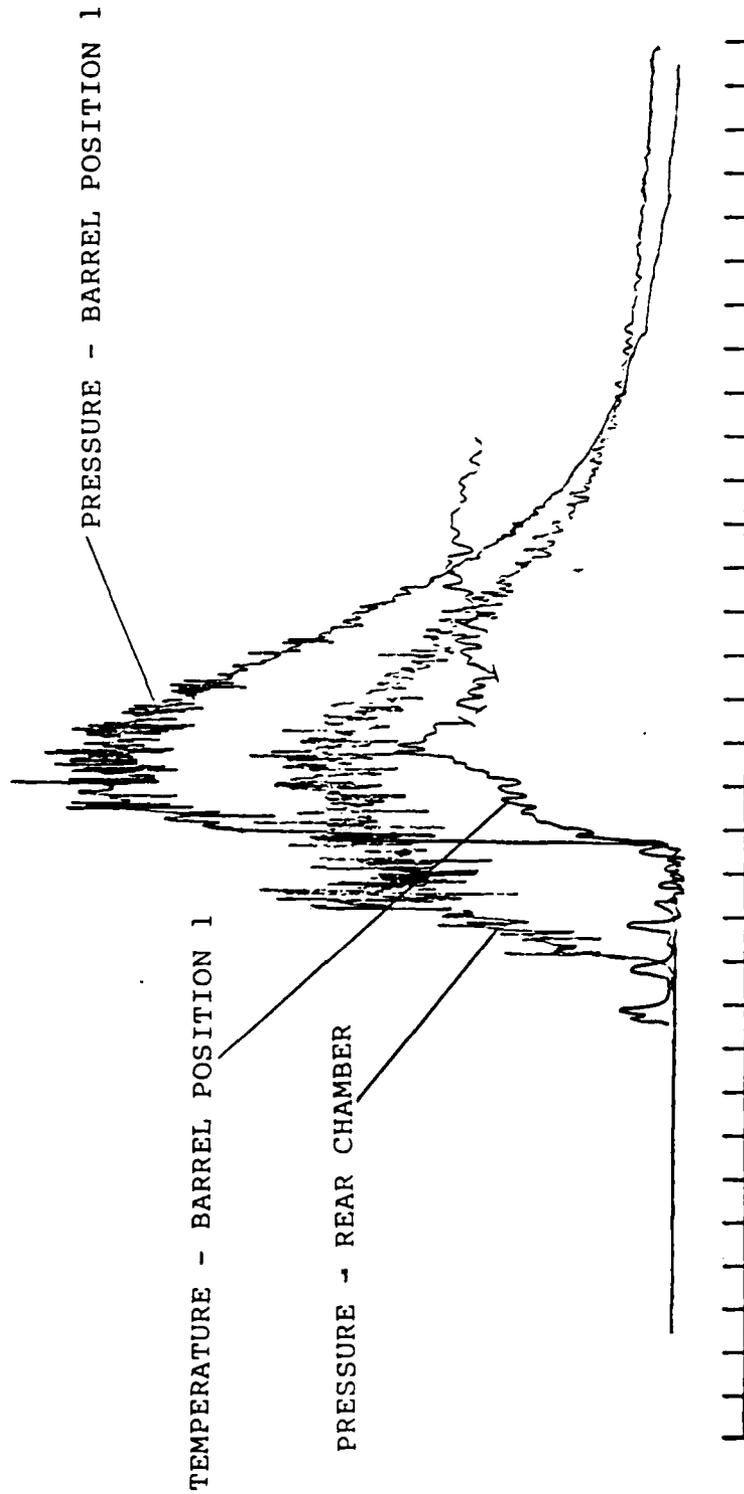
Figure 22. Simultaneous Pressure-Temperature Results For Test No. 19

scattering effects in the camera optical path, and these can seriously degrade the quality of photographic results.

For these tests the camera was mounted behind a sheet steel barricade. Its lens looked via reflection in a front surface mirror through a magnifying element and a sapphire window directly into the chamber of the ignition fixture.

Considerable exposure and timing difficulties were encountered, but useful framing results were achieved on test No. 15. A full sequence of thirty-three (33) half-frame pictures were obtained. This indicates a total self-luminous combustion time of about 2.2 milliseconds, which correlates well with the duration of the high pressure region indicated by transducers mounted to sense combustion pressure in the chamber. This sequence indicated a relatively strong, non-homogeneous, self-illumination issuing from the combustion inside the chamber. The regions of strong illumination were predominantly toward the breech and toward the bottom the chamber. Some variations in illumination occurred with time in various locations throughout the chamber. No indications of specific combustion wave propagation were observed.

Specific attempts were made in tests Nos. 13 through 16 to obtain high speed framing photographs of the early-time development of ignition and combustion. These were run using pure oxidizer in the chamber, with the intent of capturing the self-illumination due to the hot primer gas and the residual burning of this primer gas in the oxidizer rich environment. The goemetrical arrangement for capturing these results was less than ideal, since the primer issued near the chamber and the region photographed through the window was somewhat farther forward in the chamber. It was anticipated that the primer induced illumination should still have been observed; it was not, on any of the tests.

An additional attempt was made in test No. 20 to capture this same type of information with the framing camera using a backlighted view in the chamber. The chamber was filled with an oxidizer only. A General Electric 1000 watt Parlamp was used as a backlight through polycarbonate (rather than sapphire) windows. The lighting in this case was apparently insufficient to achieve useful backlighted phenomena.

Tests Nos. 17 and 18 were run together with the camera in the space-time shared streak mode, with the camera directed through a magnifier to enhance image size on the film. The HYCAM camera was equipped in this case with an f/4.5, 80-200mm, Focal brand, zoom lens. The lens was operated with the aperture fully open and the lens focal length at its maximum. A sixteen element wide aperture mask located at the magnifier, was essentially in focus with the interior of the chamber and covered the complete window diameter.

Test No. 17 was run with only oxidizer in the chamber, and gave no useful results. Apparently, the amount of self-illumination was insufficient, as it was for analogous runs made in the framing mode.

Test No. 18, was run with a full liquid propellant in the chamber. The space-time shared streak photograph in this case was properly exposed and was spread over a length of about 2 inches (50mm) along the film. Some variations in streak detail with time were observed; these presumably represented corresponding changes in self-illumination of combustion phenomena occurring in the chamber. Sufficient detail and image resolution was not available to make a full analysis of the photographic data.

In anticipation of such reductions, a further modification which was made in the LED timing-marker circuitry of

the HYCAM camera, permitted the recording of optical timing marks along the edge of the film with relatively close separation for improved film analysis. The camera circuitry was bypassed, and the LED light source was driven continuosly with an external oscillator. For the present tests an oscillator frequency of 50 kHz was used, together with pulse shaping circuitry to yield a light-on duty cycle of approximately ten percent.

Test No. 19 was essentially a repeat of test No. 18, except that the streak mask was placed over the barrel window, with the object of examining the traveling charge phenomena. Again the previous test, a properly exposed, streak photograph was observed with some detail, but without sufficient image resolution to warrant analysis of the photographic data.

Section 7.0
INSTRUMENTATION CONFIGURATION EVALUATIONS

The results of the current instrumentation configuration investigation demonstrate the suitability and utility of both pressure and thermal sensors, and indicate considerable promise for both high speed framing and streak photography for use in conjunction with LP gun phenomena assessment.

It is apparent that additional technique development is required to gain more useful and consistent data from pressure transducers. The efficacy of transducer acceleration compensation is unknown and needs to be evaluated. A need also exists to subject the pressure time data to Fast-Fourier-Transform analysis to recover frequency spectra.

In the thermal sensor area, the current surface thermocouple unit needs further calibration of both the output and time response to enable the data it generates to be more reliably interpreted. Both temperature rake type sensors and/or additional numbers of temperature sensors could make temperature a much more useful data element. If sufficiently short time response can be achieved, a Fast-Fourier-Transform analysis of time dependent thermal data could be a significant adjunct to the pressure information.

Additional types of thermal sensors, such as heat-flux meters and in-wall thermocouples, to indicate total heat input to a chamber or barrel surface, could be useful additions to the surface thermocouple examined here. The possibility of using radiation pyrometer-type techniques should be considered, especially for considerations of combustion gas-interface examinations, flame temperature evaluation, and adiabatic heating-type explorations within LP gun systems.

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The utility of the photographic techniques explored under this effort are believed to be quite promising, but the investigation still is considered to be incomplete.

Examination of the high-speed, framing-type photography has many merits in the sense of obtaining complete, two-dimensional pictures of phenomena over a short time history. The techniques required to capture the sequential development of combustion and possibly hydrodynamic wave features with time has not been fully developed under this program. We have confidence that this is still a viable avenue of investigation.

The principal shortcoming of straightforward high speed photography with a relatively inexpensive framing camera, such as the HYCAM 16 mm system used here, is the limitation on framing speed, and particularly on exposure duration. For some low-light-level phenomena, the relatively long exposure times are suitable and desirable; for high-light-level phenomena, shorter exposures could be advantageous. A general observation made of the high speed photographic system used here is that much more attention needs to be given to firmly mounting and securing the camera so that camera motor acceleration and run-up to high speeds does not cause excessive vibration, with an attendant loss in photographic image resolution (not film resolution). The use of film with higher ASA ratings could also be helpful in low-light-level situations.

The technique of space-time shared streak photography introduced here is new to us and may be new to the ballistics instrumentation community. While additional technique development is obviously required beyond the brief investigation started here, this avenue has the potential advantages of obtaining better space and time resolution of high-speed phenomena than is possible with a framing camera running at the same film speed. This resolution, of course, is obtained at the

expense of a complete two-dimensional photograph of an event that is obtained via the framing mode.

The investigation conducted here lacked sufficient image resolution on the film. The basic requirement in this case was to be able to revolve about 3.5 line pairs per millimeter. This requirement is not severe, but was not achieved, we believe, largely due to camera vibration. Some additional improvements in aperture selection for the streak exposure masks, the use of a more light sensitive film, and additional magnification of the image size would all be expected to contribute favorably to the success of this technique.

Analysis and interpretation of the streak technique, although not addressed specifically under this program, is an important consideration. For example, further attention needs to be given to the development of mask patterns and readout schemes which can facilitate the conduct of such analysis.

The elements selected herein for an instrumentation configuration are believed to be quite appropriate for further effort even though complete verification of their utility remains to be shown.

Section 8.0

CONCLUSIONS

The following conclusions have been reached based on the work completed thus far:

1. A baseline instrumentation configuration suitable for investigating a range of liquid propellant gun phenomena, and in particular, for visualizing the evolution of the gross features of internal combustion phenomena has been defined. This configuration consists of fast response, high-range pressure transducers; simple, fast response thermocouples such as the surface thermocouples specifically examined here; high-speed framing photography of capturing time-sequential development of phenomena; and high-speed space-time shared streak photography for assessing time sequential phenomena locally, with greater stop action capability than typically achieved with the same camera when using the framing mode of photography.

2. The breadth of the instrumentation configuration examined and its overall potential capability is superbly suited to the collection of critical data needed to define and serve as inputs to modeling efforts of LP guns.

3. The 25 mm LP ignition test fixture, configured for dynamic loading, bipropellant operation, and for use with various sensors appears to be a useful and controllable "workhorse" type system suitable for LP gun phenomenology investigations. This LP ignition fixture is capable of being adapted to a full gun configuration by mounting a barrel on the front of the main body component, in place of the short barrel extension currently employed.

4. The use of special test fixtures to facilitate the exploration of particular LP gun phenomena is a viable avenue. This approach is illustrated in the current program by the use of a transparent injection fixture to examine phenomena associated with injecting bipropellants in an LP gun chamber.

5.   The introduction and use of a computer based firing and timing system has been shown to be particularly beneficial to LP gun phenomenology investigations.

6.   The introduction and use of transparent high-pressure resistant windows both in the LP gun chamber and barrel is advantageous in that is enables phenomena to be visualized sequentially as it moves from the chamber to the barrel. Likewise, reverse interactions can also be examined.

7.   Preliminary LP ignition test firings have revealed what appear to be the first instances of significant traveling charge phenomena in an LP gun system.

Section 9.0
RECOMMENDATIONS

As a result of this investigation, it is recommended that the several components of the instrumentation configuration delineated herein be evolved and applied further in a Phase II program to produce a practical system for collecting critical data on liquid propellant gun systems and their controlling phenomena. This is expected to impact the timely and efficient development of suitable models to characterize LP gun performance, and thereby supply an important augmentation to LP gun development efforts.

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